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A Simulator of An Alternator
For Use with a Network Analyser

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A SIMULATOR OF AN ALTERNATOR FOR USE WITH A NETWORK ANALYSER

BY

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An investigation carried out under
the direction of Prof. J.A. Harle

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UNIVERSITY OF ALBERTA

DEPARTMENT OF ELECTRICAL ENGINEERING

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A SIMULATOR OF AN ALTERNATOR FOR USE WITH A NETWORK ANALYSER

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INTRODUCTION

Modern power systems with many generating stations and load points, often interconnected by long transmission lines are faced with possibility of unstable operation, usually brought about by transient conditions due to faults on the system. Unstable operation will cause the system to fail as a power transmitting link, disrupt service and possibly cause serious damage.

Some factors entering into the stability problem are system layout and impedances, loading, type and location of faults, the methods and speed of clearing faults and machine characteristics such as inertia, excitation, reactances and the presence of damper windings.

Simple stability problems may be handled mathematically but laboriously through network reduction and "point by point" swing calculations. Beyond two and three machine problems the complexity of the solution increases rapidly even for steady state calculations.

For this reason network analysers have been developed and used. The network analyser is a scale model of the system to be represented, allowing the rapid determination, by measurements, of voltages, power flow and currents at any point in the system. However, swing calculations are still carried out by "point by point" methods, requiring -

1. Reading the power flow and power angle of each machine.
2. Calculation of acceleration speed and change in power angle during a short interval of time.
3. Manually resetting the power angles of the machines and repeating the process until the stability of the system is determined.

Obviously this process is time consuming. The problem, then, is to extend the analogue by using a generator simulator which behaves, under all conditions, like the machine under consideration. That is:

(a) Its power angle" or rotor position must "swing" or change automatically to satisfy the "swing" equation (damping neglected)

$$M \frac{d^2\delta}{dt^2} = \Delta P$$

Where M = angular momentum of the machine and its prime mover.

δ = power angle

t = time

ΔP = $P_i - P_o$ where P_i is the shaft input to the generator and P_o is the electrical output power depending on δ and the system layout and loading.

(b) Current and voltage must vary according to loading and under transients as they would in the alternator being represented.

(c) The simulator must have an extended time scale in order that the operator may have time to take necessary readings.

The actual internal voltage of the alternator ($\vec{E_a}$ - Diagram No. 1) is produced by the combined effects of the flux due to the D.C. field ($\vec{\phi F}$) and the flux set up by the armature current (Armature reaction $\vec{\phi_A}$). This armature reaction flux under balanced conditions is rotating at synchronous speed. This voltage is the voltage behind leakage reactance (X_ℓ). For most purposes the armature reaction effect is replaced by an equivalent reactance and a fictitious voltage ($\vec{E_d}$) is considered. Under transient conditions or unbalanced loading this is not satisfactory.

The power output of the machine may be given approximately by

$$P = \frac{E_d V_t}{X_d} \sin \delta$$

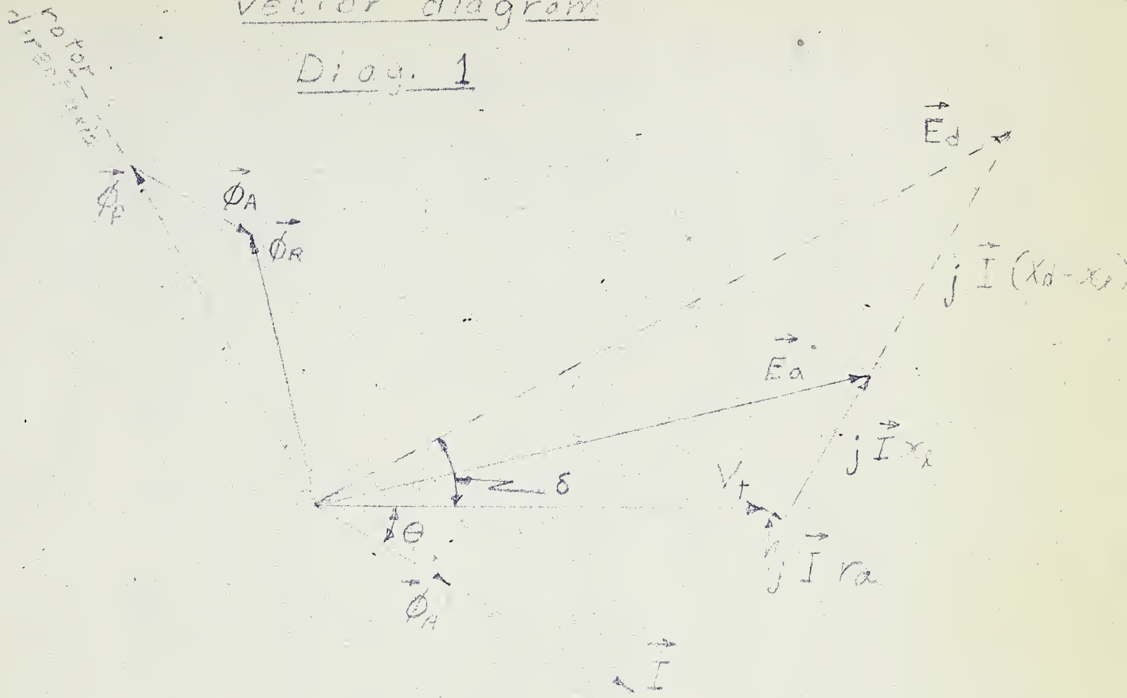
under steady state conditions. Under transient conditions the same form holds. It may be seen that the P_o is a function of $\sin \delta$ so that P_{max} occurs at $\delta = 90^\circ$ If these machines are interconnected and the angle between their rotors exceeds 90° the machines will fall out of step - one slowing due to its load and the other being accelerated by its prime moves as less power is transmitted between the machines.. This is instability.

The critical angle is not 90° for salient pole machines. Also, under transient conditions the critical angle may be exceeded on a swing without instability.

Consider an alternator feeding an infinite bus supplying power P_1 - (Diag 2). Then if the power input to the alternator is increased to P_2, its rotor will be accelerated to position δ_2 where the power output is P_2 and swing beyond this position due to inertia, until δ_3 is reached. It is then decelerated. The result is a series of swings or oscillations. If the rotor swings past δ_4 then P_2 is always greater than the output so that the rotor continues to accelerate - the system is unstable.

The alternator vector diagram

Diag. 1



$\vec{\phi}_A$ - Armature Reaction m.m.f

$\vec{\phi}_F$ Field m.m.f.

$\vec{\phi}_R = \vec{\phi}_F + \vec{\phi}_A$ - Resultant m.m.f.

$\vec{E}_a$ - air gap voltage due to $\vec{\phi}_R$

x_l - leakage reactance r_a - armature resistance.

E_d - ficticious voltage behind synchronous reactance

X_d - synchronous reactance -

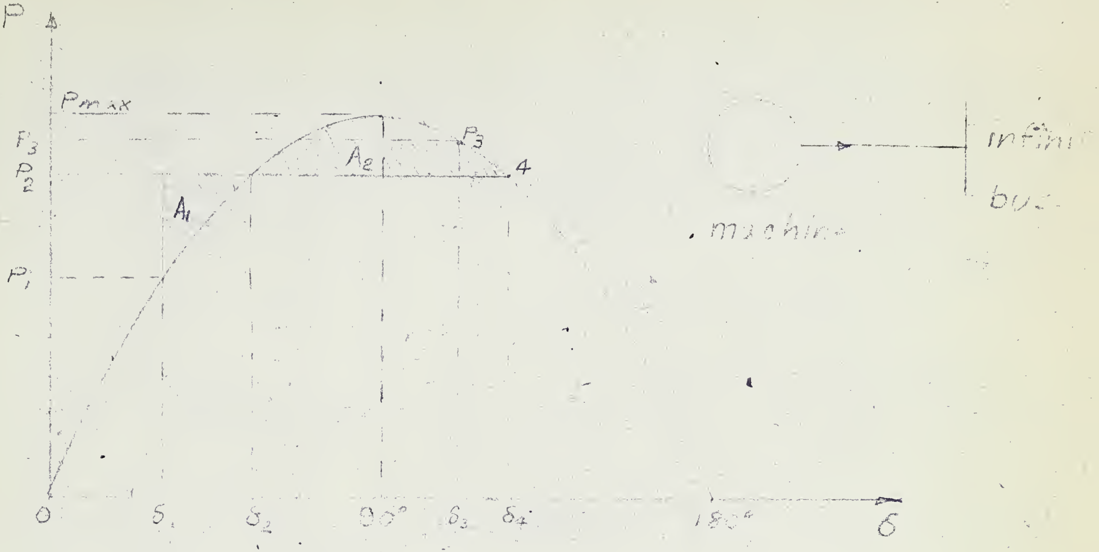
θ - Power factor angle

δ - torque or power angle.

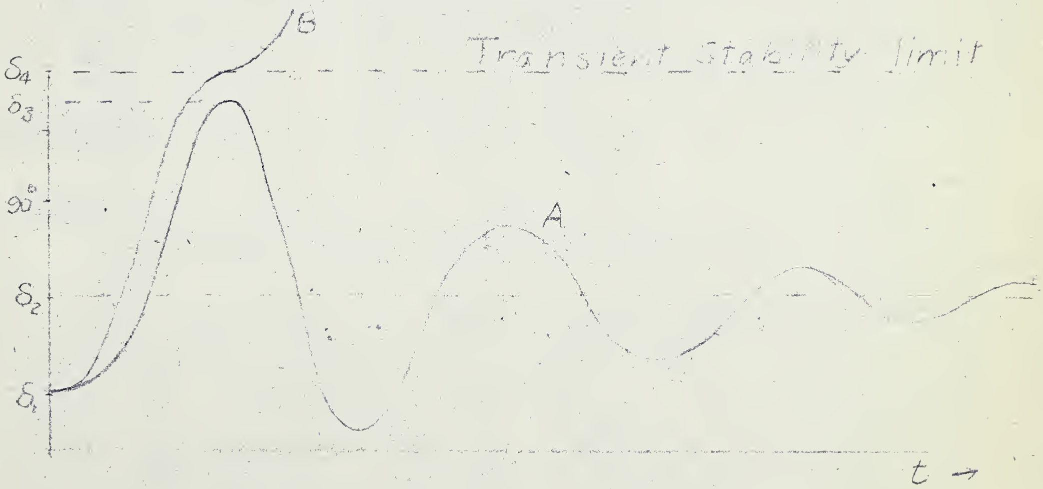
I - output-current.

V_t - terminal voltage

Diagram 2



a. Power-Angle Curve
machine feeding infinite bus



b. Swing Curve

A - stable
B - unstable

The rotor position is governed by

$$M\frac{d^2\delta}{dt^2} = P_{in} - P_{out}$$ (neglecting damping)

Damping does occur but is usually neglected in stability studies.

Pout is a function of the rotor position and is usually complex enough to exclude formal solution of the equation - hence point by point calculations are required.

Under a sudden fault or loading several things occur.

1. Pin-Pout changes so that the rotor is accelerated or decellerated
2. The flux $\vec{\phi}_R = \vec{\phi}_F + \vec{\phi}_A$ cannot change instantaneously so that E_a is initially the same, then falls exponentially.
3. This means that the current $\vec{I}$ rises to a high value (external impedance reduced) then decays. Since the current cannot change instantaneously a D.C. component is set up causing asymmetry. This will cause an alternating component in the field current.
4. $\vec{\phi}_A$ depends on the current and will rise and decay with it. However, since $\vec{\phi}_R$ is initially the same, a component is set up in $\vec{\phi}_F$ to balance this. As this decays, $\vec{\phi}_R$ changes causing a decay in $\vec{E}_a$ and hence in $\vec{I}$ and $\vec{\phi}_A$. In effect feedback is present. There is another feedback loop affecting the power output through ($\vec{E}_a$ & δ).
5. The leakage reactance X_ℓ will rise slightly to a new value X_d' the transient reactance. This is caused by an increase in leakage due to the increase in field current. If damper windings are present, they will also affect the reactance.

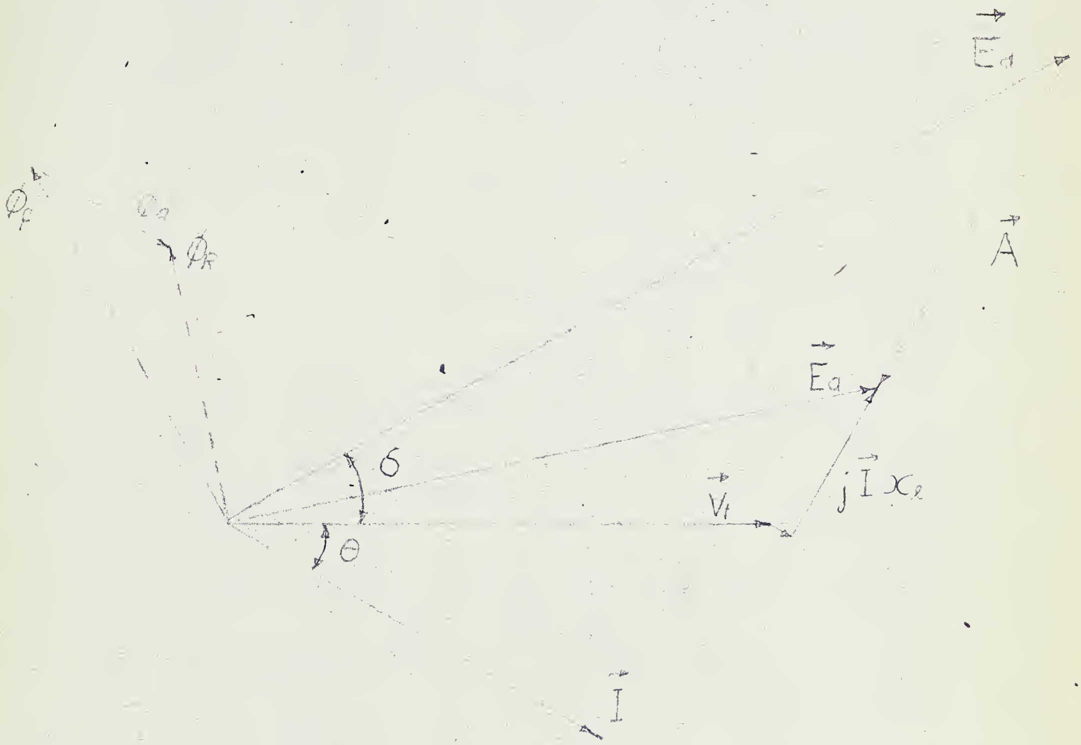
3. ASSUMPTIONS

For the purpose of this study, the following assumptions will be made.

1. There is no saturation of the iron. $\overrightarrow{\phi F}$ and $\overrightarrow{\phi A}$ may be replaced by the voltage they would produce acting alone; $\overrightarrow{E_d}$ and $\overrightarrow{A}$ respectively. Under steady state conditions $\overrightarrow{A}$ may be taken as $-j\,\overrightarrow{I}\,(X_d - X_\ell)$. This assumption will introduce some errors, especially under steady state operation. This assumption is usually made.
2. The machine has a smooth rotor. This is again a common assumption used to eliminate the complications of the two-reactance method.
3. The field flux $\overrightarrow{\phi F}$ is coaxial with the rotor direct axis - δ is a measure of the rotor position. This assumption is implicit in the swing equation.
4. $\overrightarrow{\phi F}$ is constant under transient conditions and $\overrightarrow{\phi A}$ is dependent on the current, changing exponentially on a sudden change in current, so that $\overrightarrow{\phi R}$ behaves as in the actual machine.
5. Armature reaction shall be treated as if it was independent of the type of loading - that is - it shall be considered as a sinusoidal flux rotating at synchronous speed. This is not true but the simplification is worth the cost of any errors involved.
6. The transient reactance X_d' will be assumed equal to the leakage reactance X_ℓ . The difference is negligable except in the case of a dead short circuit,. On the basis of these assumptions the following vector diagram will hold (Diag. 3).

Diag. 3

Modified Vector Diagram



4. SIMULATOR LAYOUT

The generator unit of the Contraves (Brown Boveri) analyser may be modified by -

1. Incorporating automatic control to drive the phase shifter so that the swing equation may be satisfied.
2. Injection of a voltage $\vec{A}$ to simulate the effect of armature reaction. This voltage must rise or decay exponentially with a change in magnitude or phase of the current.

In general the modified vector diagram (Diag. 3) will hold true.

As far as possible the modifications will use equipment similar to that in the basic Contraves unit and a minimum of changes will be made in the basic unit.

The block diagram (Diag. 4) gives the general layout.

5. PHASE SHIFTER OR δ UNIT

Requirements

The power angle δ of the actual machine is given by:

$$M \frac{d^2\delta}{dt^2} = \Delta P = P_1 - P_0$$

(damping and asynchronous torques neglected)

$M = J\omega$

where J = moment of inertia of rotor and prime mover.

ω = angular velocity " " " " "

ω is assumed constant as changes in speed are negligible over the period of a swing.

M may be expressed as:

$$M = \frac{1.84 \times 10^{-8} (WR^2) f}{P^2} \quad \text{megajoule-sec/elect. degree}$$

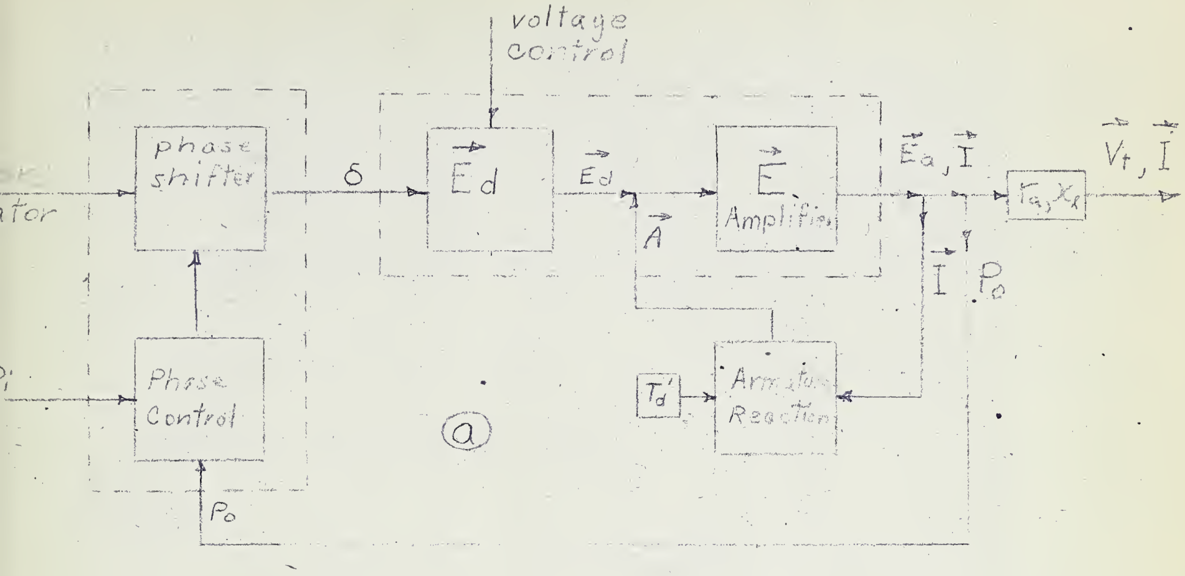
$$= \frac{GH}{180 f}$$

where G = generator rating MVA

H = inertia constant - megajoule-sec/MVA

f = frequency

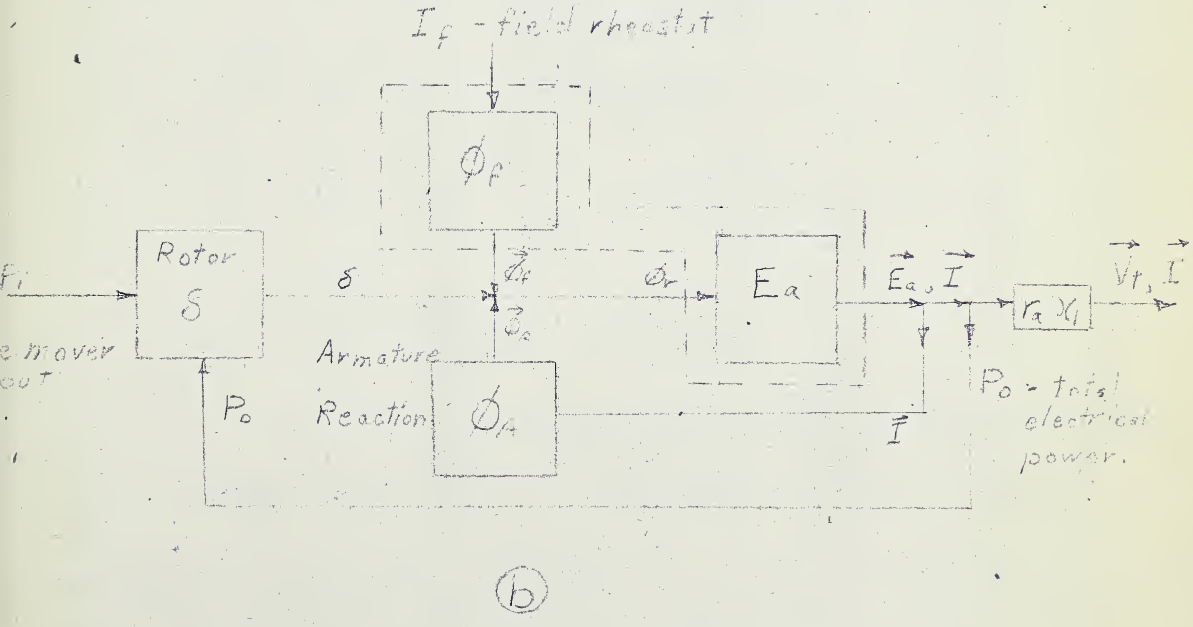
Diagram 4



Block Diagrams

a - simulator

b - alternator



On a per unit basis

$$M\ (pu) = \frac{M}{\text{Base MVA}}$$

In general M (p.u.) will fall between the limits of $10^{-5} - 10^{-2}$ (Diag.5)

Two ways of representing the swing of the machine are:

a. Use of a separate, miniature machine whose behaviour is governed by the swing equation and measuring its angular position with respect to a reference vector rotating at constant speed.

b. Modification of the transient behaviour of a motor so that its motion is governed by the swing equation.

METHOD A

The unit may be broken up into sections as shown in the block diagram (Diag. 6).

(i) Swing unit - giving solution of the swing equation.

The "prime mover" input P_i is fed to element No.1 of a two element watthour meter (Diag. 7), so that its torque is proportional to P_i. The light load adjustment is set so that the element is driven at a constant speed ω_0 for $P_i = 0$ as metered on the input wattmeter. The required value of P_i is set by use of the input wattmeter and a "dummy" load.

The torque output

$$T_1 = k\ P_i$$

Element No. 2 is supplied, through current and potential amplifier, (Diag 8), from the output of the simulator so that

$$T_2 = k\ P_o$$

in opposition to T_1

$$T_1 - T_2 = \Delta T = k \Delta P'$$

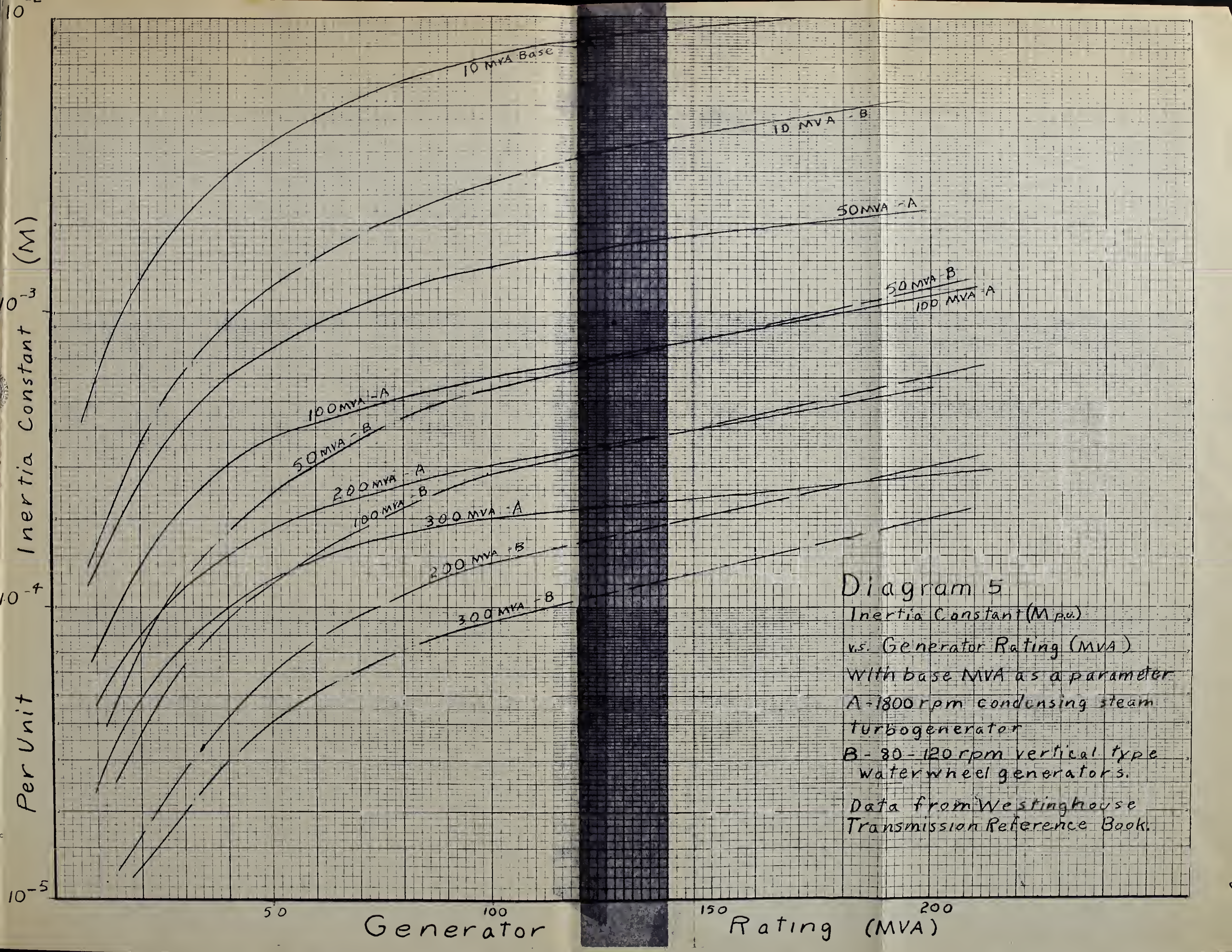


Diagram 5

Inertia Constant (M p.u.)

v.s. Generator Rating (MVA)

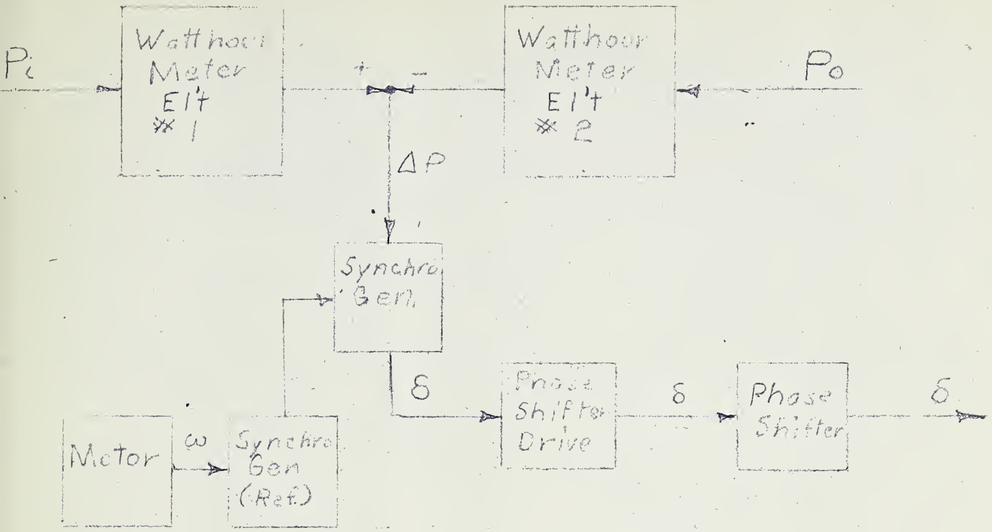
With base MVA as a parameter

A - 1800 rpm condensing steam turbogenerator

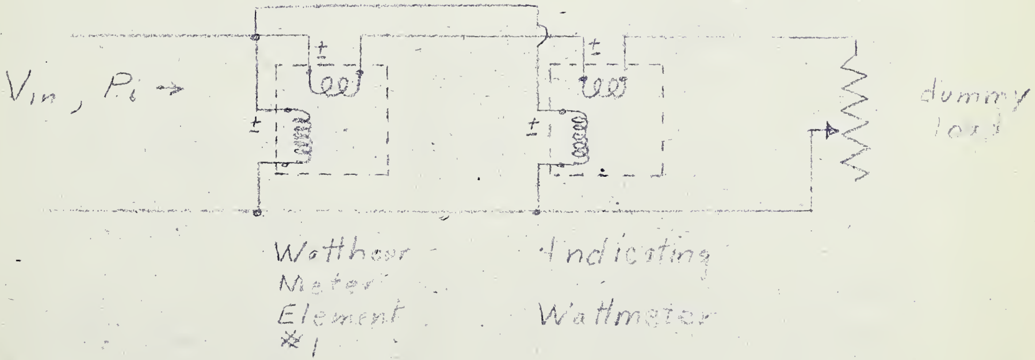
B - 80 - 120 rpm vertical type waterwheel generators.

Data from Westinghouse Transmission Reference Book.

Diag 6 - Block Diagram of swing unit



Diag 7 Electrical Layout Element ※1



Neglecting damping torque (register and drag magnets removed and the meter running at slow speed.)

$$J \frac{d^2\theta}{dt^2} = \Delta T$$

$$J\omega \frac{d^2\theta}{dt^2} = \omega \Delta T = \Delta P$$

$$\Delta P = \Delta P_{pu} \; G A_v A_i$$

where ΔP_{pu} = per unit change in power of the machine being represented

G = base power of simulator

A_v = voltage amplifier gain

A_i = current amplifier gain

$$\Delta P = (\omega k G A_v A_i) \; \Delta P_{pu}$$

$$M = J\omega = M_{pu} \; G A_v A_i$$

$$M_{pu} \frac{d^2\theta}{dt^2} = \omega k \Delta P_{pu}$$

$$M' = \frac{M_{pu}}{\omega k}$$

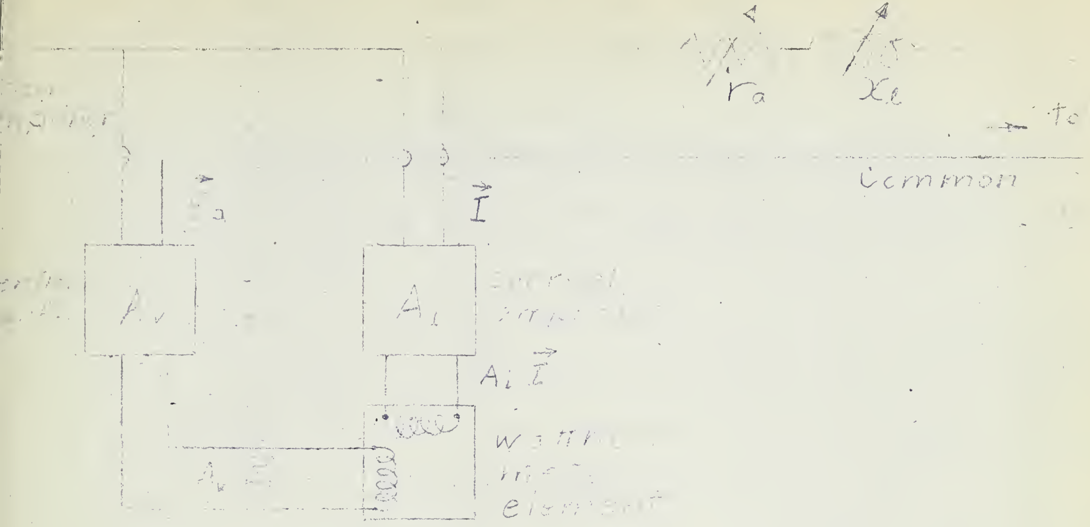
$$J' = \frac{M_{pu}}{\omega^2 k}$$

for an expanded time scale Ts $\left(\frac{\text{sec}}{\text{sec}}\right)$

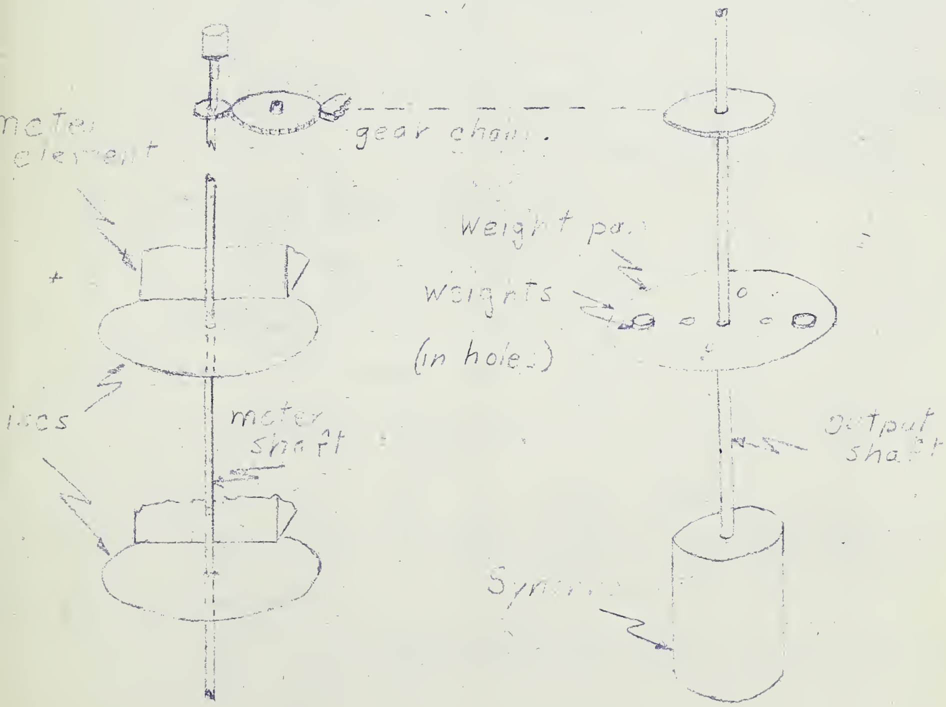
$$J' = \frac{M_{pu} T_s}{\omega^2 k}$$

Thus, given M (p.u.) of the machine to be represented the equivalent M' of the simulator may be set by control of J' - the moment of inertia of the simulator. This may be done by adding weights to the output shaft of the meter (diag. 9).

Diag 8 Element # [illegible]



Diag 9 - A possible physical layout



(ii) Detection & transmission of Angle

The output of the above elements gives

$$\varphi = \omega t + \theta$$

To detect θ a reference at constant speed ω is required so that the angular difference θ may be measured. This may be done in several ways.

(a) By means of a mechanical differential - this is awkward physically and reflects loading and inertia effects back to the swing unit.

(b) By means of a synchro mesh - There are several variations possible but the system which appears to be the best is:

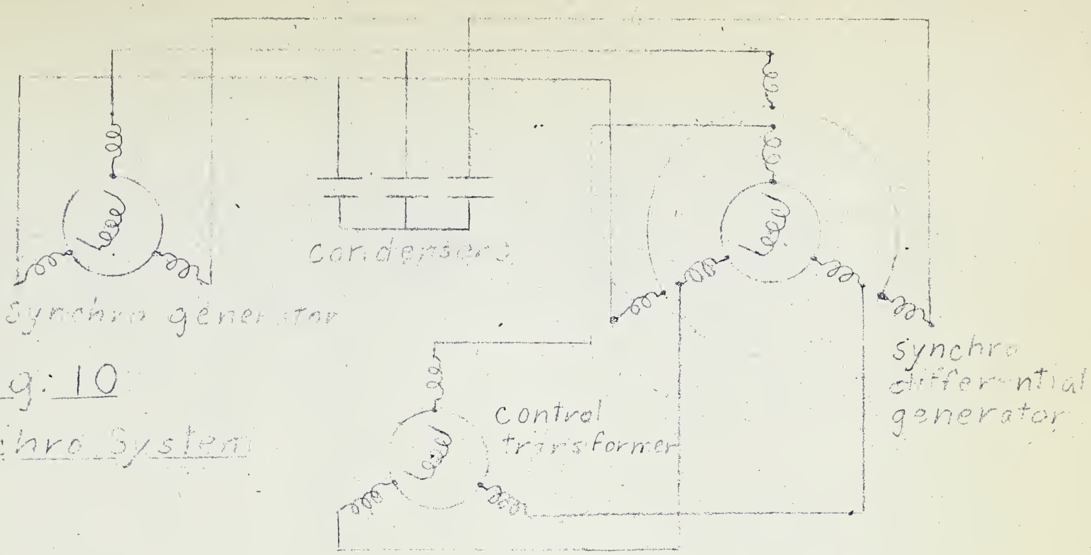
1. The swing element driving a differential generator
2. The reference unit driving a synchro generator which supplies one set of windings on the differential unit. (Diag. 10). This unit may be large enough to be a common reference for the whole analyser.
3. The difference signal may then be sent to a control transformer or a synchro repeater depending on the phase shifter drive.

(iii) Control of the phase shifter

The phase shifter output δ must be kept in 1:1 correspondence with θ as given by the swing unit. This would require modification of the Contraves unit so that it is linear and 360° mechanical rotation produces 90° electrical rotation. That is a 4:1 speed ratio between the output shaft of the phase shifter and the shaft of the swing unit. There must be negligible loading and inertia affects fed back to the swing unit.

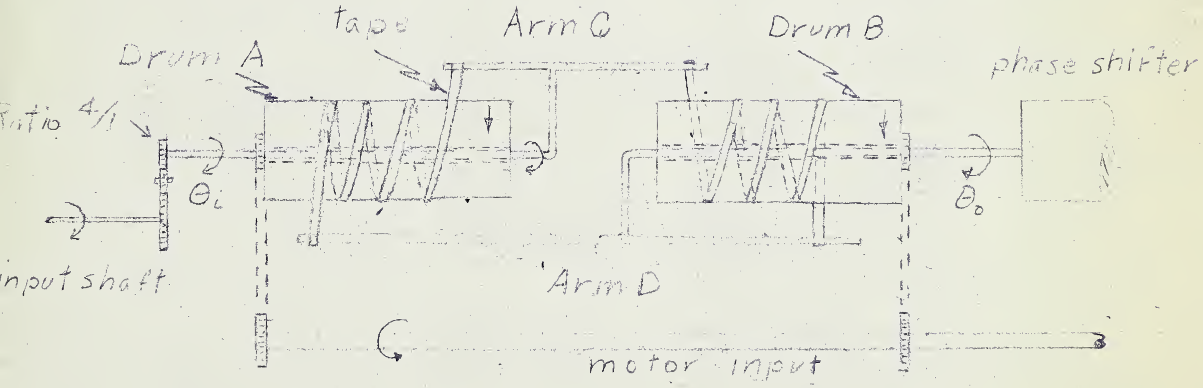
(a) If the output from the detection unit is given as a shaft rotation it may be used by:

1. A capstan-type torque amplifier (Diag 11). In this system a motor drives both drums at a constant speed. Clockwise



Diag: 10
Synchro System

Diag 11 Capstan type torque amplifier



rotation of the input shaft moves arm C clockwise, tensioning the tape on drum B. The tension in the tape builds up exponentially along its length so that a much greater force is exerted on arm D moving it and the output shaft clockwise until $\theta_o = \theta_i$. Counter clockwise rotation is effected by drum A. Torque ratios of 80:1 to 100:1 are possible in a compact unit. However care must be taken in adjusting the tapes and, for this application the over-all unit may be too bulky to fit into the generator drawer. However, remote operation is possible.

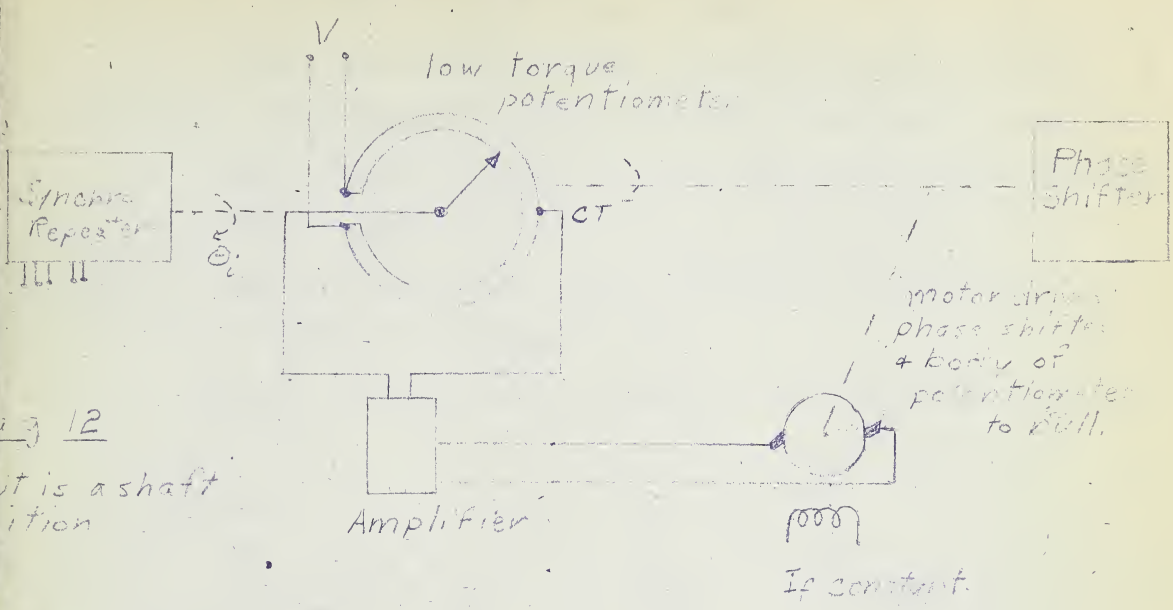
2. The output shaft could drive the wiper of a low torque potentiometer which would pick off a voltage proportional to the shift from a null position (Diag. 12). This voltage may then be amplified and used to drive a shunt or a 2 phase A.C. motor geared to the phase shifter. The body of the potentiometer would also be driven towards a null position. This system would tend to keep the output angle equal to the input since the correction signal (hence speed) is proportional to the error. The system may be classed as a type 2 servomechanism having, inherently, no positional error. Velocity errors would be minimized by choosing a motor with good damping and a small time constant.

(b) If the output from the detection unit is given as a voltage (synchro transformer). the system (2) above may be modified by using the error signal from the transformer to drive the motor.. Feedback would be obtained by using the motor output to drive the transformer rotor to its new null position.

This system appears to be the most satisfactory because:

(a) There would be no mechanical loading of the "swing unit"

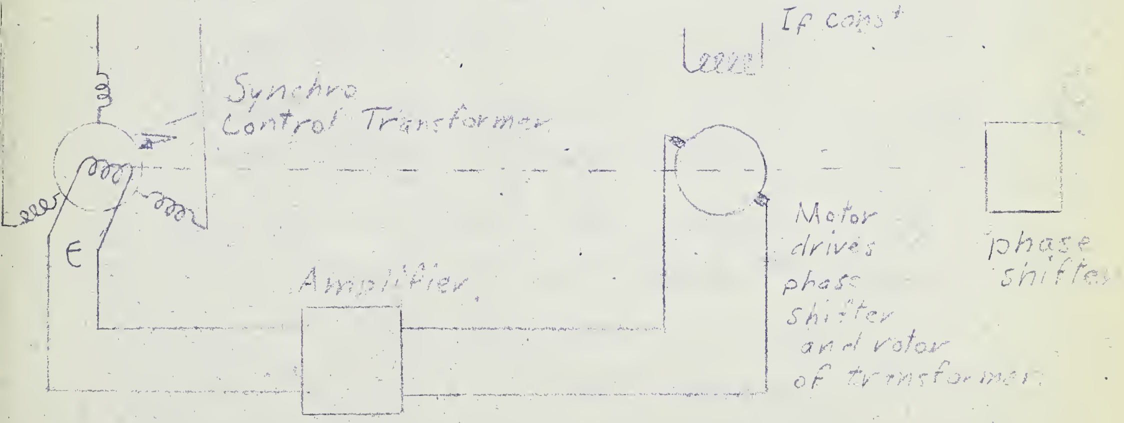
Control Units



motor drives phase shifter + body of potentiometer to null.

ig 12
ut is a shaft
ition

Diag 13 Input is a voltage (E)



Motor drives phase shifter and rotor of transformer.

N.B. 2 phase AC motors are suitable.

(b) Zero positioning problems are decreased - only one synchro unit and no potentiometers to adjust.

(c) The space requirements are less than in the other systems.

In principle, the swing unit using watthour meters elements is quite satisfactory but there are several disadvantages which would seem to eliminate its use.

1. A rotating reference is required and the unit would have to be synchronized when setting up a problem.
2. Variation in M is controlled by varying the moment of inertia of the swing unit.

As an example:

$$J' = \frac{M_{pu} T_s}{\omega^2 k} \qquad T_s = 200 \text{ say}$$

$$M_{pu} - 10^{-5} \rightarrow 10^{-3} \, \frac{\text{joule}}{\text{watt}} = 10^{2} - 10^{4} \, \frac{\text{gm cm}}{\text{sec}^2\text{-watt}}$$

$$\omega = 5 \text{ rpm} = 30 \, {}^{\text{deg}}/_{\text{sec}}$$

$$k \approx 10 \, \frac{\text{gm-cm}^2}{\text{sec}^2} / \text{watt}$$

$$\text{Then } J' \approx 2 \text{ to } 200 \text{ gm cm}^2$$

These values are extremely low and it is doubtful whether they could be obtained. A decrease in W. and increase in K could be obtained through gearing. J would then be referred to the output, slow speed shaft. This would increase J to a practical value but gearing losses and static friction effects might crop up.

In any case, the adjustment of weights to vary J may be awkward as it could not be done from the front of the panel.

3. The detecting network may cause loading errors.
4. The synchro network may not have as high an accuracy of resolution as required although higher errors may be tolerated than in a static device. Errors of 1 - 2% may occur in the detecting network only.
5. The no load speed adjustment may drift.
6. The meter elements would be operating at 500 cps and would have to be adjusted for that frequency. If a meter designed for 60 cps is used, not

all frequency caused errors may be compensated.

7. Physically the unit is bulky.

METHOD B - Use of a motor as a combined swing unit and drive unit (Diag. 14)

i. Detection of ΔP

The term $P_i - P_o = \Delta P$ may be detected and converted to a shaft rotation by a two element wattmeter with the elements connected in opposition. Element No. 1 would produce a torque proportional to P_i which may be measured on a separate, indicating meter and controlled with a "dummy" load (Diag. 15). The second element, would produce an opposing torque proportional to P_o - supplied from the output of the simulator (Diag. 16).

Under steady state conditions $\Delta P = 0$ so that there would be no deflection. Under swing conditions $\Delta P \neq 0$ so that there is deflection. This rotation of the meter shaft would drive the wiper of a low torque potentiometer away from its null position picking off a voltage proportional to ΔP .

ii Swing Unit

The voltage from the potentiometer may then be amplified and used to supply a shunt motor (fixed field) driving the phase shifter.

Change of position of potentiometer wiper

$$\theta_i - \theta_o = r \, \Delta P$$

where $r =$ (degrees/watt) constant of meter (linear scale)

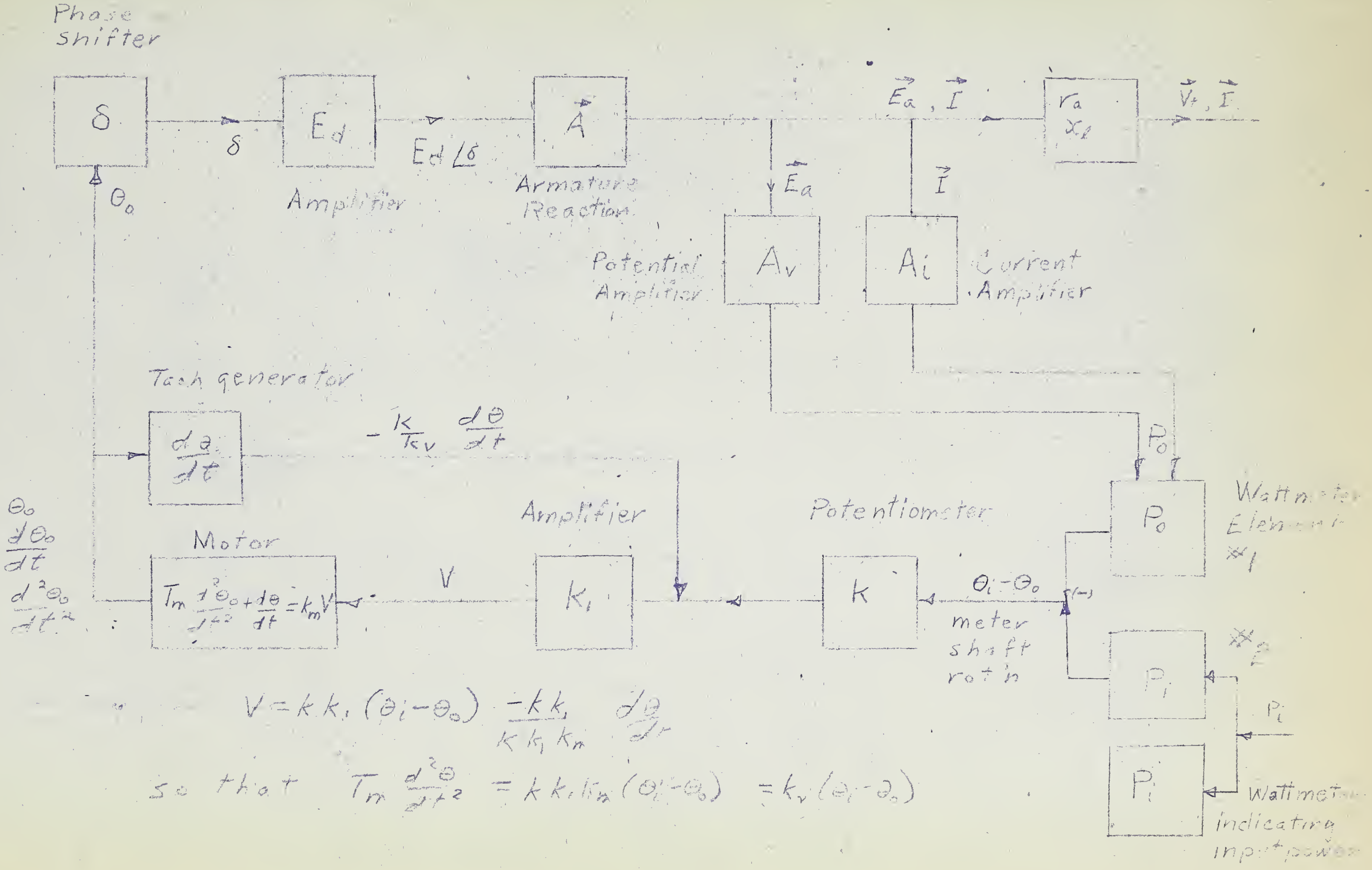
The voltage output is $k(\theta_i - \theta_o)$

After amplification we get

$$V = kk_1(\theta_i - \theta_o) = krk_1 \, \Delta P$$

Under transient conditions the motor shaft position is governed by

$$J \frac{d^2\theta_o}{dt^2} + \frac{k_t}{k_m} \frac{d\theta_o}{dt} = k_t V$$

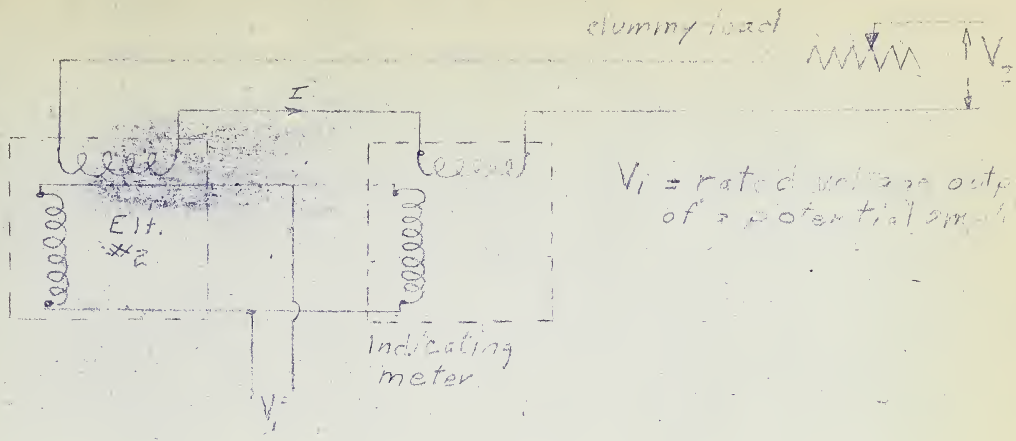


$$V = kk_1(\theta_i-\theta_o) \frac{-kk_1}{kk_1k_m}\frac{d\theta}{dt}$$

so that $T_m\frac{d^2\theta}{dt^2} = kk_1k_m(\theta_i-\theta_o) = k_v(\theta_i-\theta_o)$

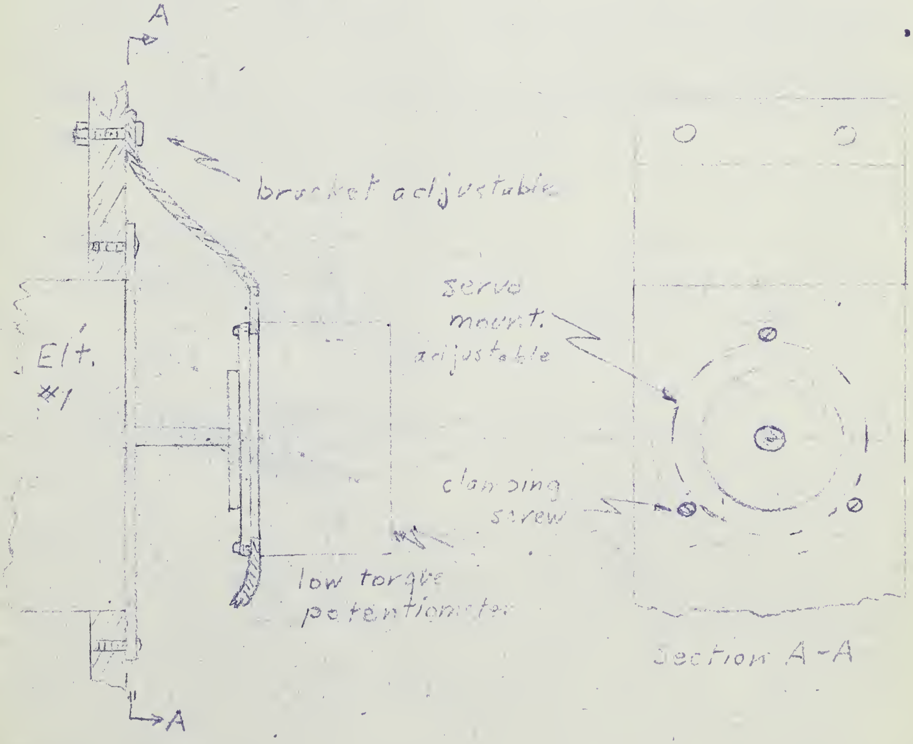
Diag 14. Block diagram - System B.

Diag 15 Wattmeter element #2 (P



V_1 = rated voltage output of a potential ampli

Diag 16 -Mounting of potentiometer



J = moment of inertia of rotating assembly

K_t = stalled torque constant (torque/volt)

K_m = speed constant (degrees/volt)

All values are referred to the phase shifter shaft with the load connected.

Motor time constant $T_m = J \frac{k_m}{k_t}$

$$T_m \frac{d^2\theta_o}{dt^2} + \frac{d\theta_o}{dt} = k_m V$$

if a speed term $\frac{1}{k_m} \frac{d\theta_o}{dt}$ is included in V

$$T_m \frac{d^2\theta_o}{dt^2} = k k_1 r k_m \Delta P$$

$$\frac{T_m}{k k_1 k_m r} \frac{d^2\theta_o}{dt^2} = \Delta P$$

but $\theta_o = N\delta$

Where N = 1/4 if the phase shifter output is directly proportional to input rotation and 360° mechanical rotation gives 90° electrical rotation.

This is the swing equation.

where $M' = \frac{T_m N}{k k_1 k_m r} = \frac{NJ}{k k_t k_1 r}$

If ΔP = per unit watts

K = (volts/degree) of potentiometer

K_1 = amplifier gain (volt/volt)

R = (degrees/watt (p.u.)) of meter

K_t = (torque/volt) constant of motor

J = moment of inertia of motor, gearing and phase shifter

M = the per-unit angular momentum

M_{pu} may then be controlled by

1. The voltage across the potentiometer.
2. The amplifier gain.

iii Control of the phase-shifter.

The phase shifter may be driven by the motor through gearing. Feedback is obtained through the variation of ΔP with δ . This is analogous to the alternator. The Contraves phase shifter must be modified, however, to give a linear relation between δ and shaft position.

iv The velocity or damping term in the motor equation may be eliminated by use of a tachometer generator.

It should be noted that the swing equation neglects damping which does exist in practice. This damping can be provided and controlled by control of the feedback from the tachometer generator. Critical damping could be used to speed up the operation of setting loads and pre fault conditions.

The advantages of this system over the previous system are -

1. All controls can be made "front panel" controls.
2. The value of J is not critical - in fact it should be large. Also it is not varied.
3. Load torque effects are not as critical
4. No rotating reference is required.
5. Wattmeters suitable for the job are standard units.

CONSTRUCTION

(a) The current and potential amplifiers and the meter movements should, as far as possible, be of the standard types used in the Contraves analyzer. However the wattmeters used must meet the following requirements:

1. A uniform scale - preferably 270° for greater sensitivity.
2. Since ΔP may be $+ve$ or $-ve$ the zero point must be offset towards

mid scale but no more than 170° (preferably 150°) from the far end of the scale because the potentiometer null position at the center tap and rotation either way must be limited so that the wiper never reaches a dead zone.

Full scale reading should be the minimum consistent with possible values of ΔP. This is unlikely to exceed ± 5 (pu) For example: ±5pu - 270° rotation → 27° per pu. power

(b) The power input (P_i) must have the same scale and movement as the P_o element. It may be supplied from a separate source and connected to a variable "dummy" load (Diag. 15). It is advantageous to use a separate meter to indicate P_i but use could be made of the meter on the output side switching it in while setting loads.

This requires that the dummy load is supplied with current and voltage of the same order as met in the output circuit.

The best construction would be that of a two-element wattmeter, without a scale but having a long shaft.

(c) The potentiometer should be a low torque, linear unit with a center tap. It should be mounted so that the body may be rotated for accurate zeroing. (e.g. Servo mounting - possibly as in Diag. 16). The resistance should be high, as greater linearity is obtainable for a high resistance potentiometer.

A suggested unit is the Helipot Model T

1/2 watt

400V max

360° mechanical rotation (continuous)

355° ± 0° - 5° electrical rotation

Linearity tolerance ± 0.5% (standard

± 0.25% on order (10000 Ω or up)

Starting torque - 0.005 oz-in

Running torque - negligable

J - 0.000377 $gm\text{-}cm^2$

Shaft Diameter - 0.0780"

Servo mounting and Ball bearings.

The potentiometer may be supplied with a fixed or variable voltage. A fixed voltage is preferable in that "M" is controlled by the amplifier gain, only.

(d) Velocity feedback may be obtained from a tachometer generator driven by the motor and supplying a voltage proportional to velocity. Part of this voltage may be used to control damping - which can be made variable. To increase damping when "setting up", a reversing switch may be used in order to boost natural damping if this is required. (Diag. 17)

Also, for convenience in "setting up", the full voltage across the potentiometer could be applied to the amplifier in order to obtain higher motor speed. (Diag. 17).

(e) The output angle of the contraves phase shifter is not a linear function of the input angle so that

$$\frac{d^2\delta}{dt^2} \neq \frac{1}{n}\frac{d^2\theta}{dt^2}$$

However, the phase shifter potentiometer can be made non-linear to correct this so that

$$\theta = n\delta$$

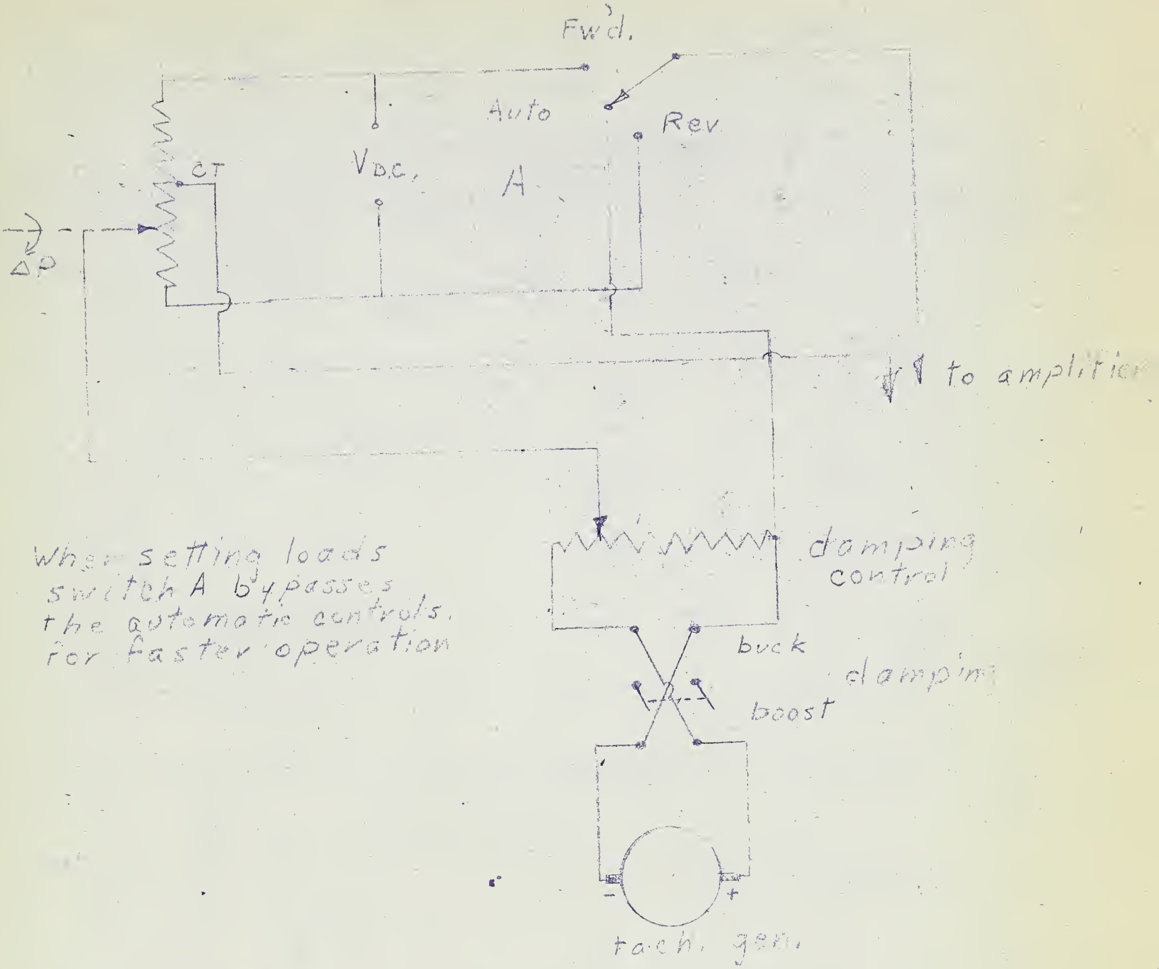
The following is an analysis of the phase shifter and modifications required so that

$n = 4$ 4° mechanical = 1° electrical

The phase shifter on the Contraves unit is in two sections:

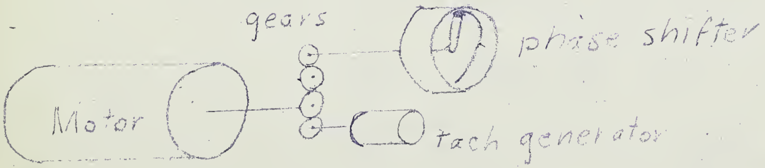
1. Auxiliary - providing 90° shift for every 360° rotation of the main phase shifter.
2. Main - giving -20° to + 87° shift for every 360° mechanical rotation. (diag. 18).

Diag 17 Control Circuit



When setting loads
switch A bypasses
the automatic controls.
for faster operation

hysical layo



This gives $\delta = 2\tan^{-1}\frac{R}{X_c}$

$$= 2\tan^{-1}\frac{r\theta}{X_c} \quad \text{where } r = \Omega/\text{degree of rotation}$$

The out put is as shown in Diagram 19a. This is not suitable for the simulator although it has the advantage that there are no "dead" regions. To modify this to give the relation shown in Diag. 19b, Xc must be changed so that $\delta = 90^\circ$ at $\theta = 360^\circ$ and by padding of the potentiometer.

Padding ;

δ	$\frac{R}{X_c}$	θ
30°	0.268	120°
60°	.577	240°
90°	1.00	360°

$$\frac{R_{30}}{R_{90}} = 0.268 \qquad \frac{R_{60}}{R_{90}} = 0.577$$

$$\frac{R_{90} - R_{60}}{X_c} = 1.00 - 0.577 = 0.423$$

If this section of the 20 $k\Omega$ potentiometer is unpadded

$$R_{90} - R_{60} = \frac{20}{3} = 6.67\ k\Omega$$

$$R_{60} = 9.13\ k\Omega$$

$$R_{30} = 4.23\ k\Omega$$

$$R_{90} = X_c = 15.8\ k\Omega$$

$$C = 0.0202\ \mu F$$

The padding resistors required (Diag. 20) are:

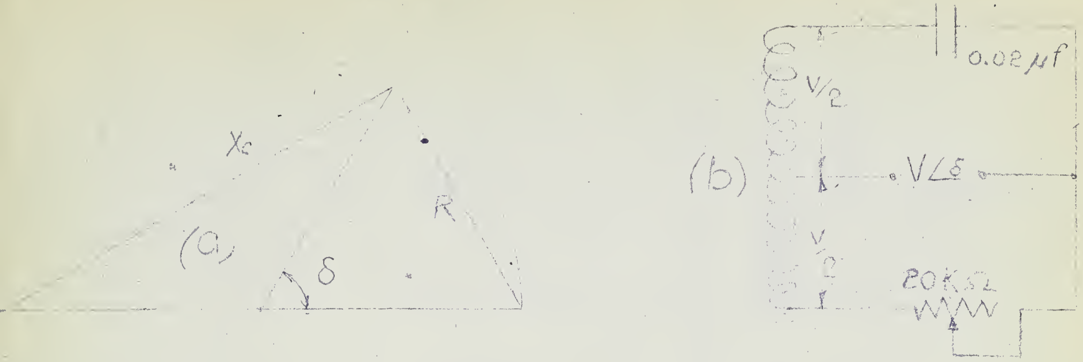
$R_1 = 11.58\ k\Omega$ - between $\theta = 0^\circ$ and 120°

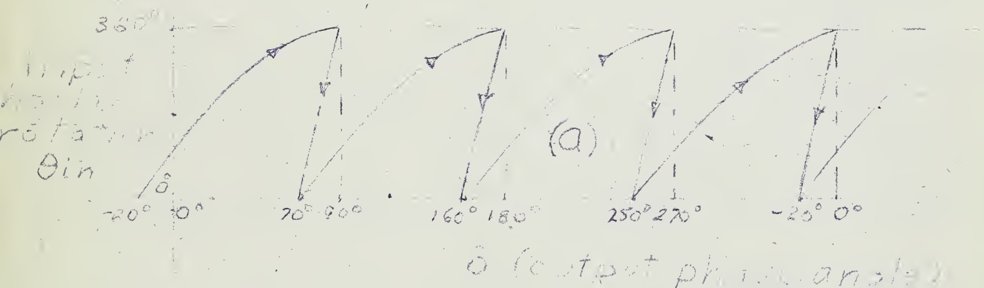
$R_2 = 18.55\ k\Omega$ " " $= 120^\circ$ and 240°

The results of this padding are shown on Diagram 20. This will give a possible error of 2% during motion, but will cause no error at standstill because of the nulling characteristics of the system.

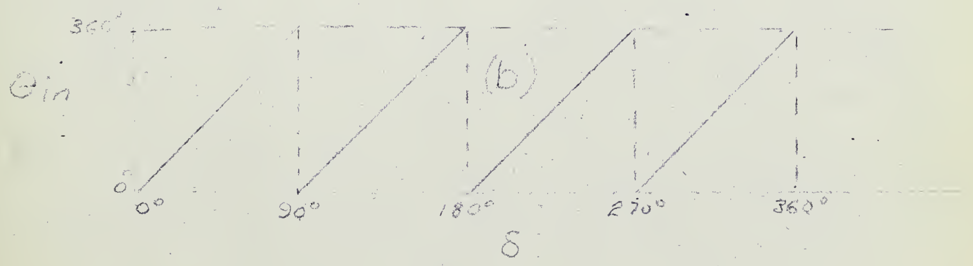
Better padding could be obtained by tapping at 60° intervals but this is not necessary.

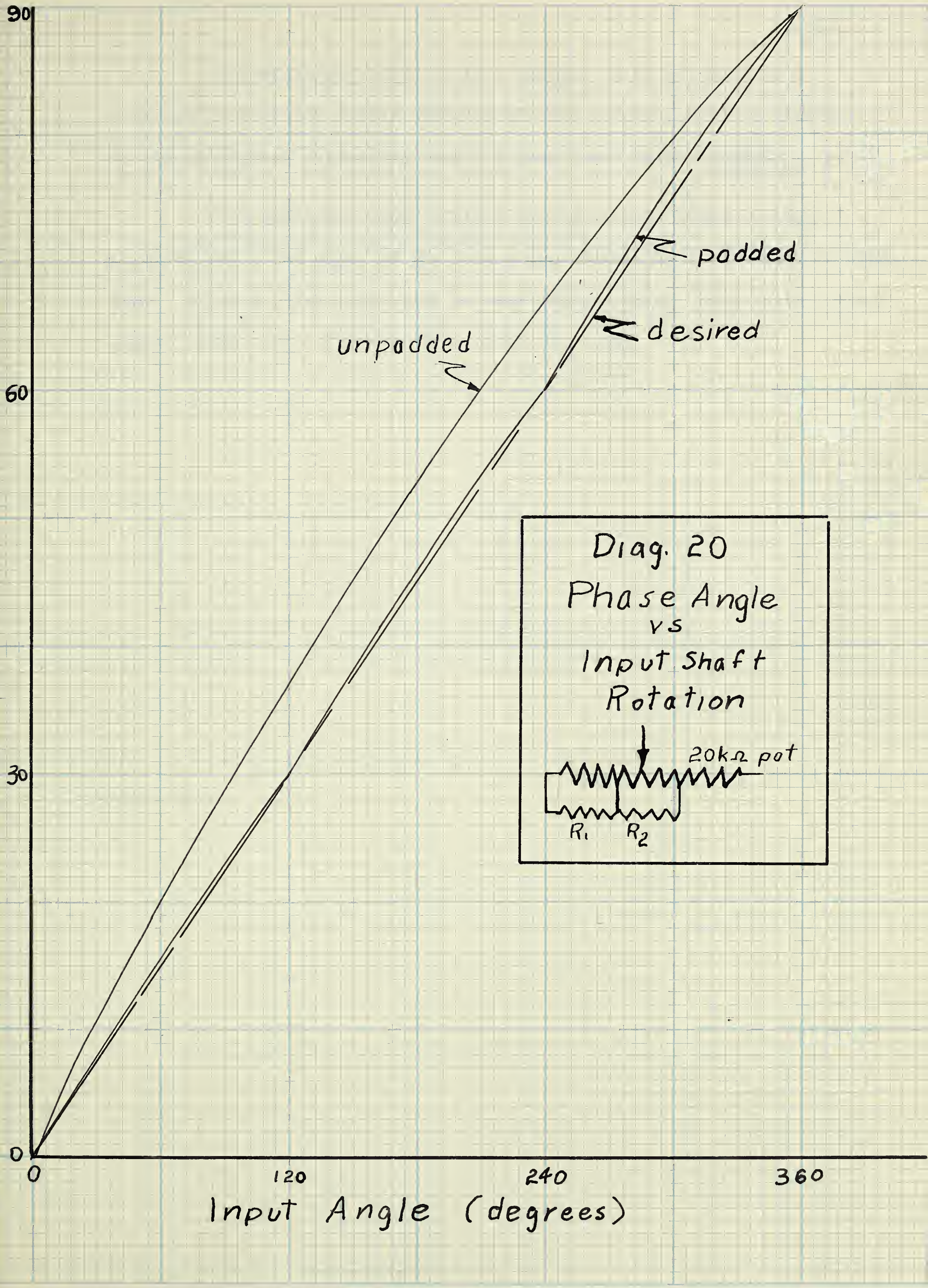
Diag 18 Phase Shifter
a - vector diagram
b - circuit





Diag. 19 - Phase Shifter position vs phase
(a) - Present Contraves unit
(b) - Desired relationship





Diag. 20
Phase Angle
vs
Input Shaft
Rotation

The auxiliary phase shifter appears to be operated by a standard 12 position rotory switch. If this is so it must be geared to the main phase shifter so that its gear tooth ratio $\left(\frac{\text{main}}{\text{auxiliary}}\right)$ is $\frac{12}{1}$

The auxiliary phase shifter should be positioned so that it operates while the wiper of the main phase shifter is in the end, or dead, zone. At this point there will be some angular error, even in the steady state. This error will be of the order of 2 - 3%.

6. ARMATURE REACTION UNIT

According to previous assumptions, the armature reaction at any load under steady state conditions may be represented by a voltage.

$$|A|\angle\varphi = \vec{A} = -j\vec{I}\,(X_d - x_d')$$

Under transient conditions the armature reaction does not change instantaneously but has rather, an exponential rise or decay.

Considering a step change in current from $\vec{I_0}$ to $\vec{I_f}$ then

$$\vec{A} = \vec{A_0} + (\vec{A_f} - \vec{A_0})\left[1 - e^{-t/T_d'}\right]$$

where $\vec{A}$ is the armature reaction at time t

$\vec{A_0}$ is the initial value $= |A_0|\angle\varphi_0$

$\vec{A_f}$ is the final value $= |A_f|\angle\varphi_f$

T_d' is the time constant of the machine including the effect of the external circuit.

The problem of representing armature reaction may be split into two subsections.

(a) phase

$$\varphi = \varphi_0 + (\varphi_f - \varphi_0)\left[1 - e^{-t/T_d'}\right]$$

(b) Magnitude

$$|A| = |A_0| + (|A_f| - |A_0|)\left[1 - e^{-t/T_d'}\right]$$

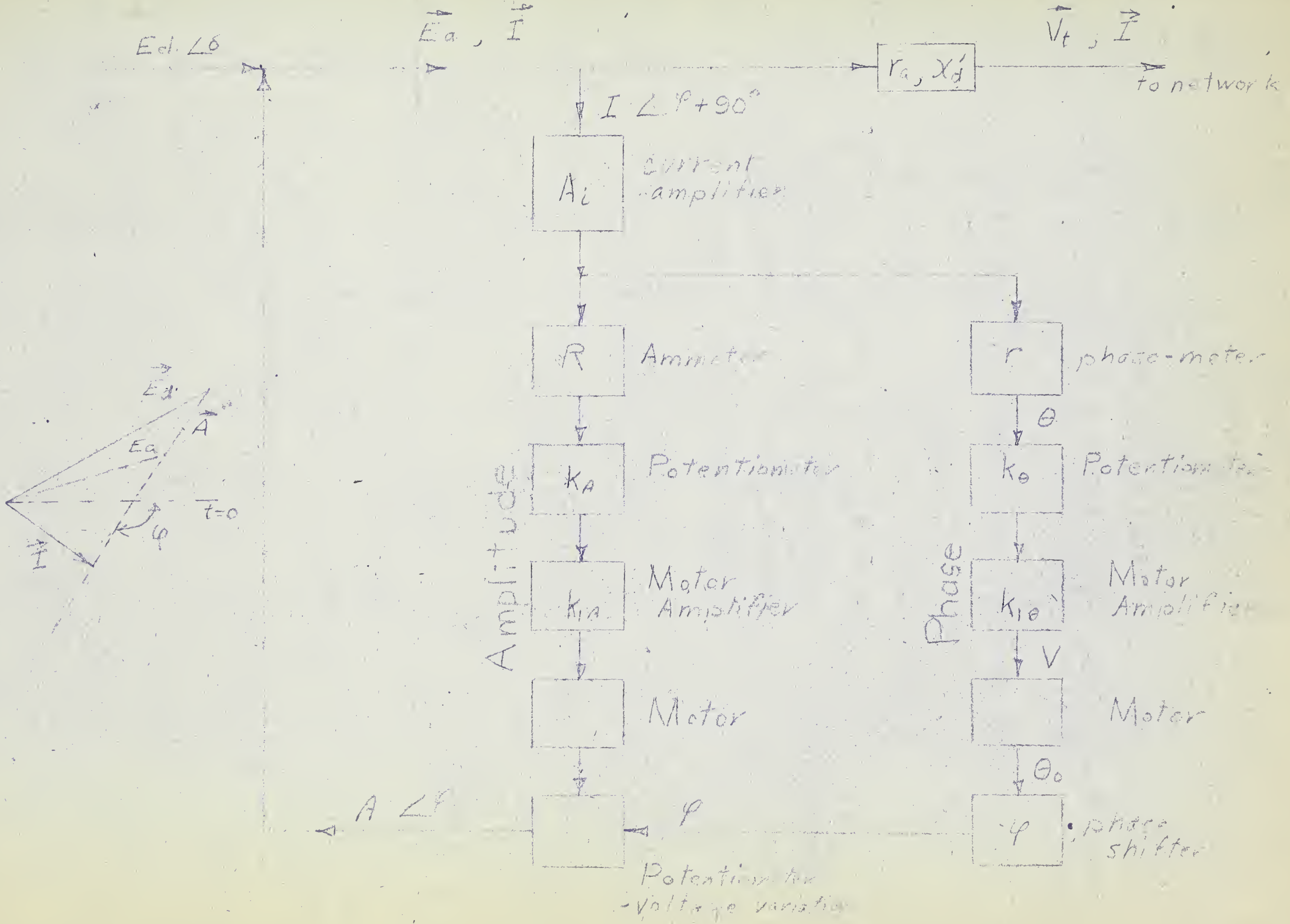
These may be handled separately with the output of a phase shifter feeding the voltage unit as in the Contraves unit. The output $\vec{A}$ is then injected into the system of the simulator (Diag. 21).

(a) Phase

The phase of the output current may be measured and indicated by the angular movement of a meter element. The meter may be a power factor meter or a synchroscope having continuous rotation and a linear scale.

The change in position of the meter shaft (on a step input) is

$$\epsilon = \theta_L - \theta_0$$



Diag E1 Armature Reaction Unit - Block Diagram

Phase angle of current $\alpha = \varphi + 90^\circ$

$$\theta_i = \alpha_f = \varphi_f + 90^\circ$$

$$\theta_{oo} = \alpha_o = \varphi_o + 90^\circ$$

The meter drives the wiper of a potentiometer away from its null position (corresponding to θ_o), so that a voltage is picked off

$$v = k(\theta_i - \theta_o)$$

This voltage is then fed to an amplifier producing a voltage

$$V = kk_1(\theta_i - \theta_o)$$

Neglecting transient phenomena, the motor speed is

$$\frac{d\theta_o}{dt} = kk_1k_m(\theta_i - \theta_o)$$

The motor then drives the phase shifter. If the output angle of the phase shifter is fed back to control θ_o (i.e. - drive the body of the potentiometer towards null) then

$$\frac{d\theta_o}{dt} = kk_1k_m(\theta_i - \theta_o)$$

$$\ln(\theta_i - \theta_o) = -kk_1k_m t + C_1$$

$$\theta_i - \theta_o = C_1 e^{-kk_1k_m t}$$

$$\text{At } t = 0 \qquad \theta_o = \theta_{oo}$$

$$\theta_i - \theta_{oo} = C_1$$

$$\theta_i - \theta_o = (\theta_i - \theta_{oo})\, e^{-kk_1k_m t}$$

$$\theta_o = \theta_{oo} + (\theta_i - \theta_{oo})\left[1 - e^{-kk_1k_m t}\right]$$

$$\text{or} \quad \varphi = \varphi_{oo} + (\varphi_f - \varphi_o)\left[1 - e^{-kk_1k_m t}\right]$$

k = volt/degree of potentiometer

k_1 = amplifier gain

k_m = degrees/sec./volt at shaft driving the potentiometer

T_s = simulator time constant

$$T_d'(\text{system}) = \frac{1}{k\,k_m\,k_1\,T_s}$$

The time constant may be set by variation of the amplifier gain.

This analysis neglects transient effects on the basis that $T_s \; T_d' >>$ the motor time constant. However the damping should be sufficient to prevent oscillation.

Using the same phase shifter circuit as in the δ unit, 90° shift between $\vec{I}$ and $\vec{A}$ may be achieved by positioning the potentiometer so that $\theta = 0$ when $\varphi = -90^{\circ}$. This may be done quite simply when "zeroing in" the unit. The gear tooth ratios required are -

$$\frac{\text{main phase shifter}}{\text{Auxiliary " \quad "}} = \frac{12}{1}$$ (directions of rotation presumed the same)

$$\frac{\text{main phase shifter}}{\text{potentiometer}} = \frac{4}{1}$$

The layout would be as in Diagram 22, 23, and 24.

The electrical layout of the phase shifter is the same as for the phase shifter in the δ unit - i.e. The Contraves unit with the modification in the phase shifter as indicated for the δ unit. (Diag. 27).

(b) Magnitude

The general layout of the drive and feedback mechanism is much the same as for the phase shifter.

The magnitude of the line current is detected by an ammeter which drives a low torque potentiometer away from its null position giving a voltage which may be used to supply the motor driving the output voltage control potentiometer as in the Contraves unit. Again, mechanical feedback may be used to drive the body of the error measuring potentiometer back towards null. This will give

$$|A| = |A_0| + \left(|A_f| - |A_0|\right)\left[1 - e^{-\frac{t}{T_d'}}\right]$$

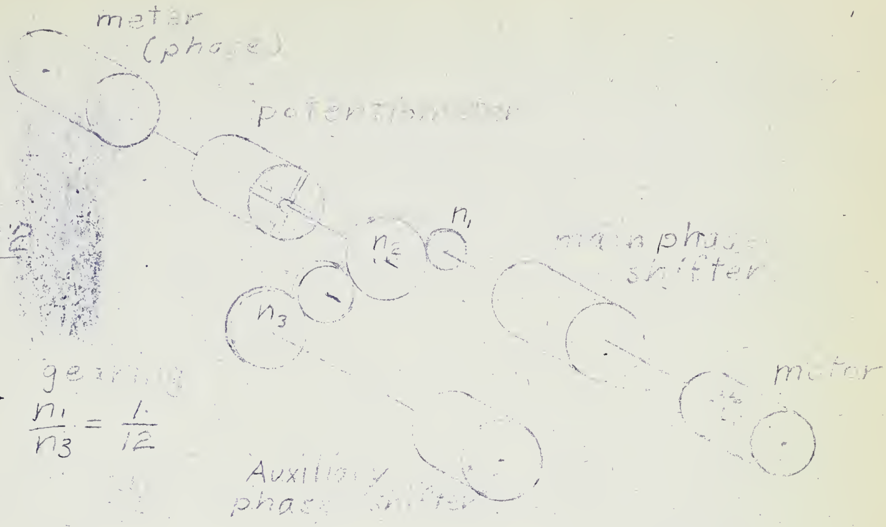
$$T_d'(\text{system}) = \frac{1}{k k_m T_s k_1}$$

The modifications required, however, are more extensive. The general layout is indicated in diagrams 25 and 26.

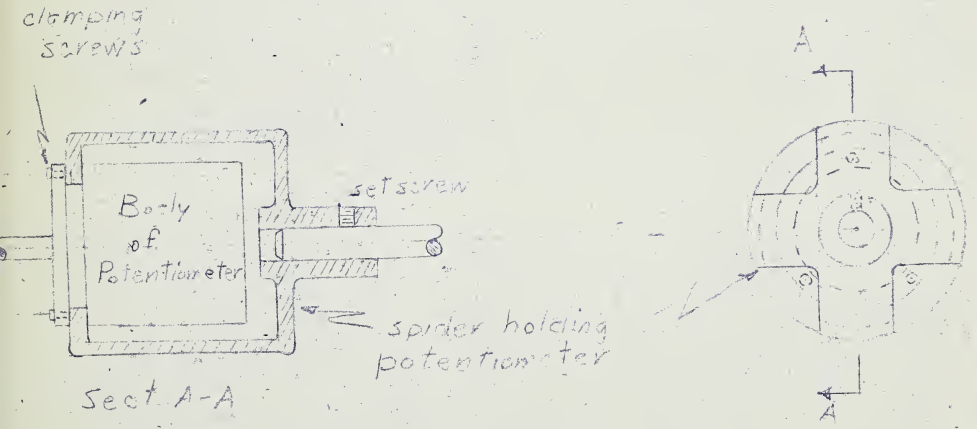
The output of the $\vec{A}$ unit may be fed into the pre-amplifier

Armature Resultant - phase.

Diagram 22

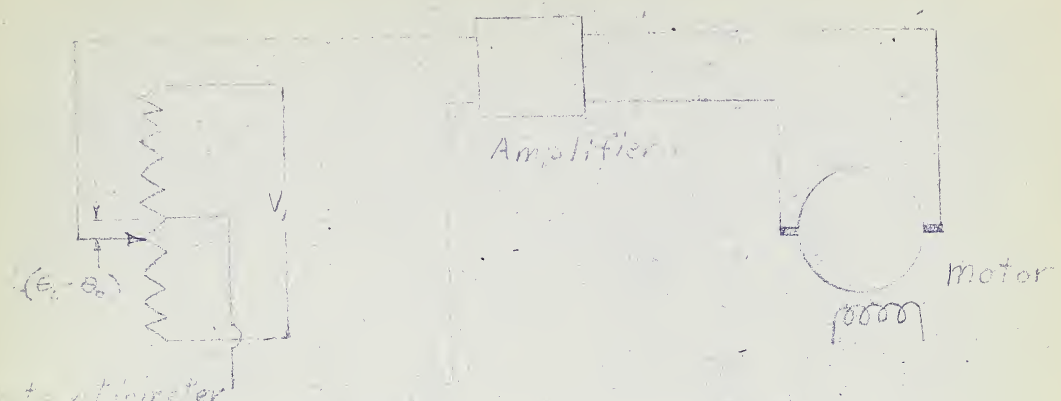


$\frac{n_1}{n_2} = \frac{1}{4}$ $\frac{n_1}{n_3} = \frac{1}{12}$



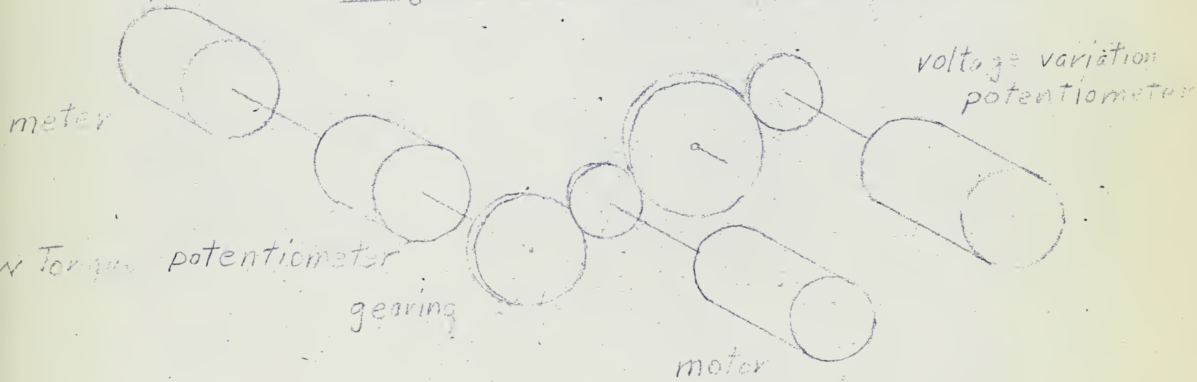
Diag 23

Diag 24 - Armature Reaction Unit (phase)

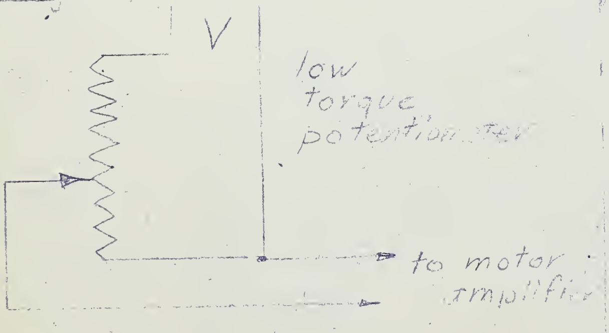


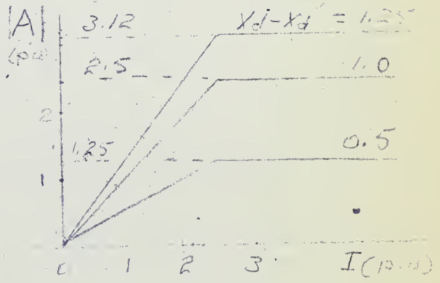
potentiometer
- nulled by mechanical feedback from the motor.
- wiper driven by phase-meter.

Diag 25 Armature Reaction Unit - Amplitude



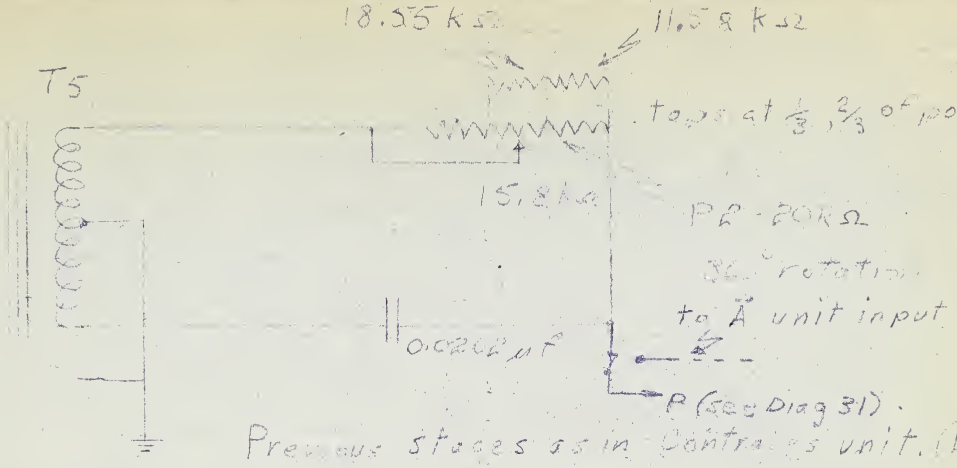
Diag 26





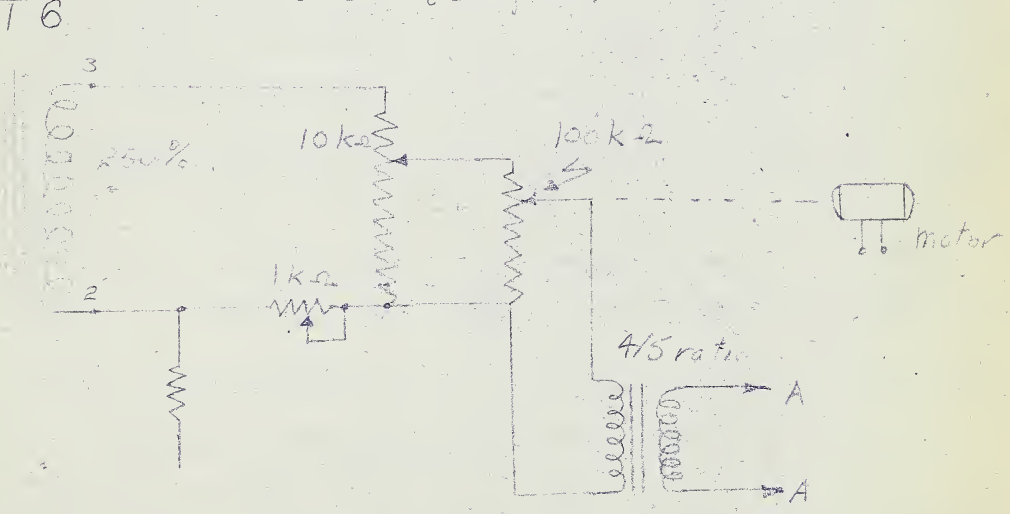
Diag 28 Variation of |A| (steady state) with current I

Diag 27 - modified phase shifter (Contd.)



Previous stages as in Contraves unit. (Diag 31)

Diag 29 - Armature Reaction (magnitude) Variation - modification of Contraves circuit (Diag 30)



10kΩ potentiometer - "Xq - Xd" variation
0 - 125%

100kΩ pot - 0 - 250% current

Output A-A injected into Contraves unit (Diag 30)
0 - 3.12 volt.

of the main unit as shown (Diag. 30). The amplitude variation circuit of the $\vec{A}$ unit may be as in diagram 29.

The 10kΩ potentiometer may be used to vary $(X_d - X_d')$. The wiper of the 500 k potentiometer is driven by the motor. The output is then controlled by

1. $(X_d - X_d')$
2. The current.

In order to limit the grid voltage at the pre-amplifier (a) should be limited to a value of 2.5 to 3 p.u. This determines the meter range and the gear ratio on the feedback.

The output of the Transformer (T6) is of the order of 2.5 p.u. The $(X_d - X_d')$ divider can be considered as having a range of 1.25 p.u. Then, with $(X_d - X_d')$ set at 1.0 p.u. the maximum output is 2 p.u. Use of a transformer of ratio 4:5 provides isolation and raises this output to 2.5 p.u. If the meter range is set at 2.5 p.u. - then, with $(X_d - X_d')$ = 1.0, under steady state conditions at I = 2.5 p.u., $|A|$ is 2.5 p.u. as required. The maximum out put is then 3.12 p.u. with $(X_d - X_d') =$ 1.25.

The gear ratio between the input potentiometer and the voltage variation potentiometer is then $\frac{360}{270} = \frac{4}{3}$ if the meter has a 270° scale and the useful rotation of the voltage variation potentiometer is 360°.

The input potentiometer does not need a center tap - The null position will be at one end.

The meter should have a range of 2.5 p.u. and preferably, a 270° scale. It must be capable of carrying up to 10 p.u. without damage.

The effect of this on $|\vec{A}|$ is shown in Diag. 28. In effect the system saturates at this value of current.

Under transient conditions this "saturation" should have little or no effect on the first and most important part of the transient. Later,

the current will probably drop below this value. The effect of this saturation may be eliminated by using a 5 p.u. meter and a 1:2 isolating transformer although this may give too high a voltage input to the pre-amplifier.

It is quite possible that under such conditions in an alternator, saturation would limit $|A|$.

7. SUMMARY

A representation of the swing equation appears to be quite feasible at a reasonable cost. However, there will be problems, requiring experimental work, in setting up the system.

Representation of armature reaction would probably cost more than it is worth. For general purposes, the swing unit alone is sufficient as the rise and decay of currents may be neglected during the period of a swing. The armature reaction unit does provide a more versatile unit and transitions from steady state to transient state operation may be handled automatically.

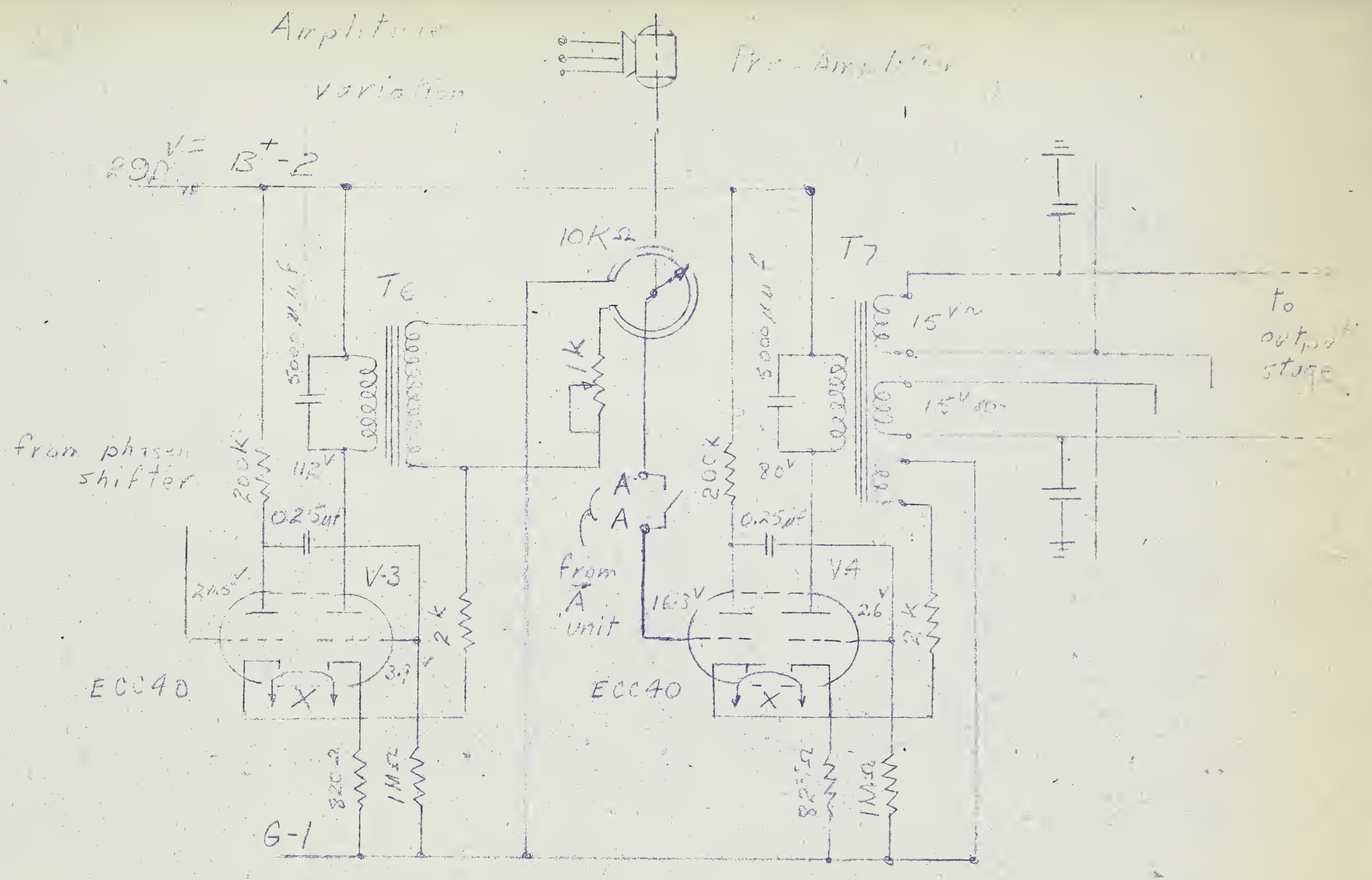
The swing and armature reaction units could be mounted in separate drawers and connected to the basic generator unit when required, or, if preferred, they need not be used.

The layouts given are such that all controls and scale settings are electrical and may be "front panel" controls for convenience in "setting up" the unit. To some extent the controls are themselves analogous to the controls of an alternator and prime mover such as steam or water inlet valves of the prime mover (P_i) and the field rheostat (voltage variation potentiometer).

It is probable that the unit may be extended to take into account factors such as governor response, voltage regulator action and saturation.

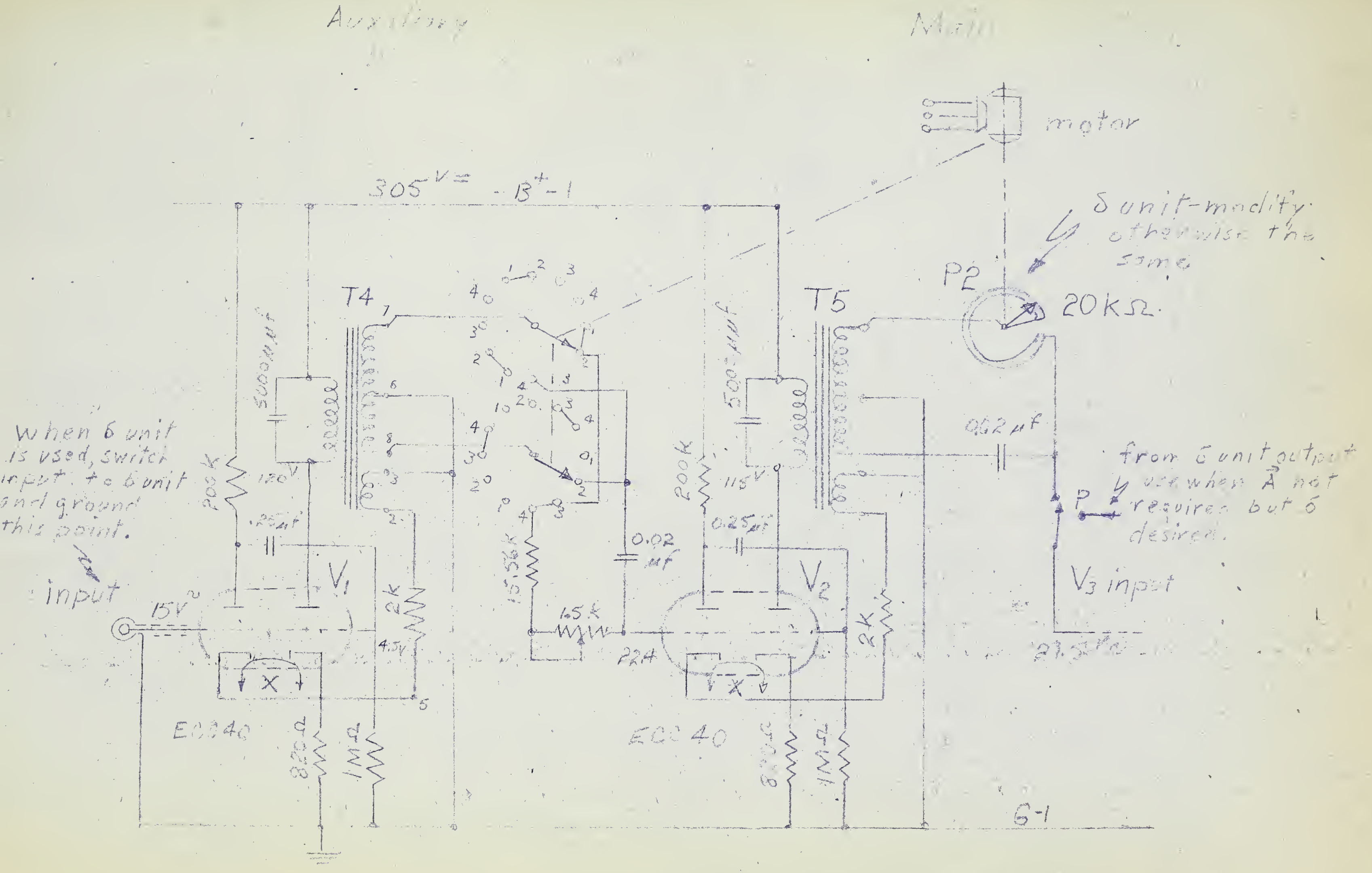
No design work could be done on the motor amplifiers, physical layout motor sizes and speeds and gear ratio, etc. because these are dependent upon the layout of the components of the Contraves unit. As much information as possible was taken from the Contraves circuit diagram including some extrapolation as to the mechanical operation of the phase shifter.

It may be noted, that, although this study is concerned with the Contraves unit, the principles could be adapted to another type of unit.



Diag 30 - Voltage variation stage of Controves unit.

$\vec{A}$ unit similar except as shown (Diag 29) - $\vec{A}$ output injected at A-A



Diag 31 Contraves Phase Shifter

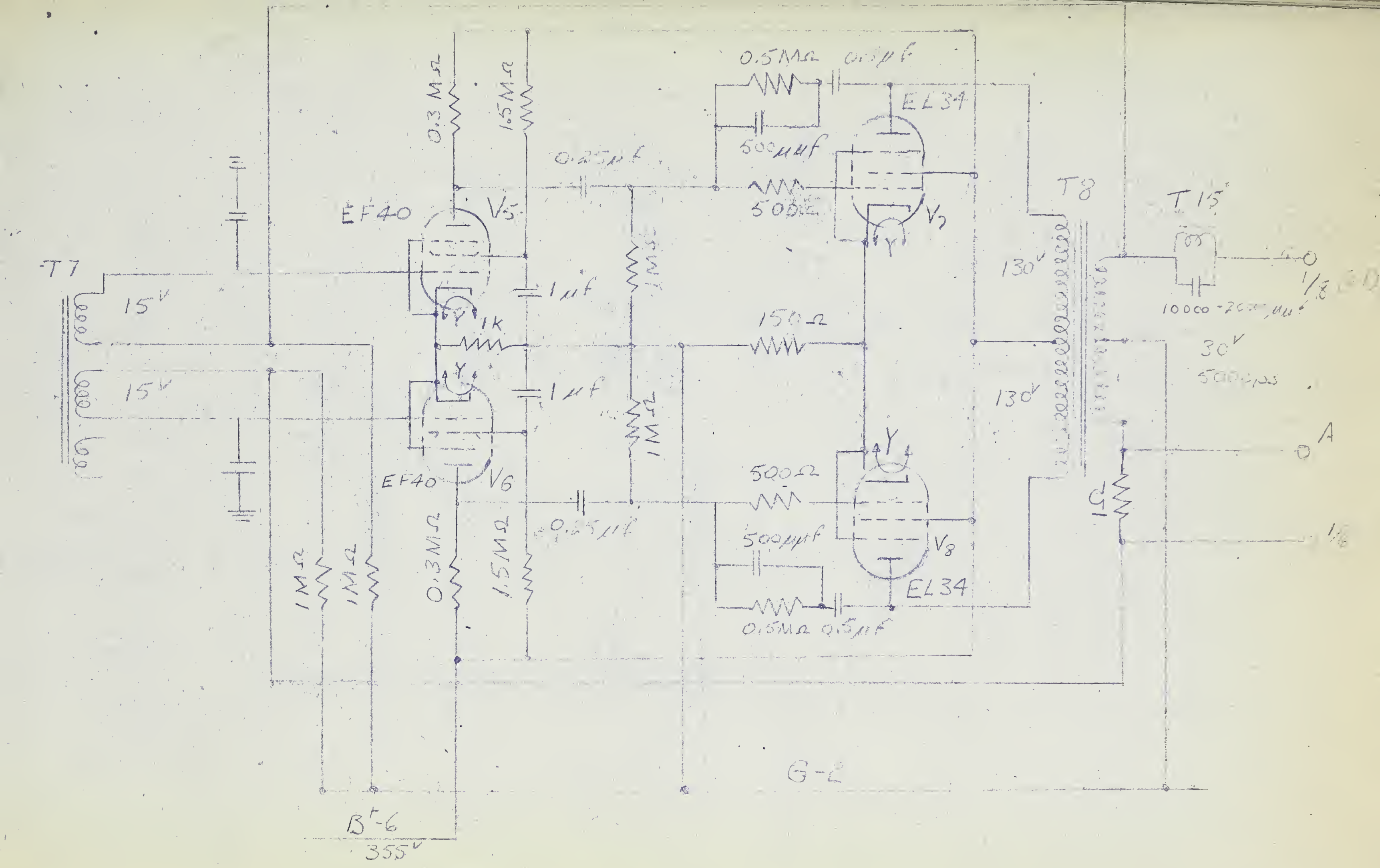
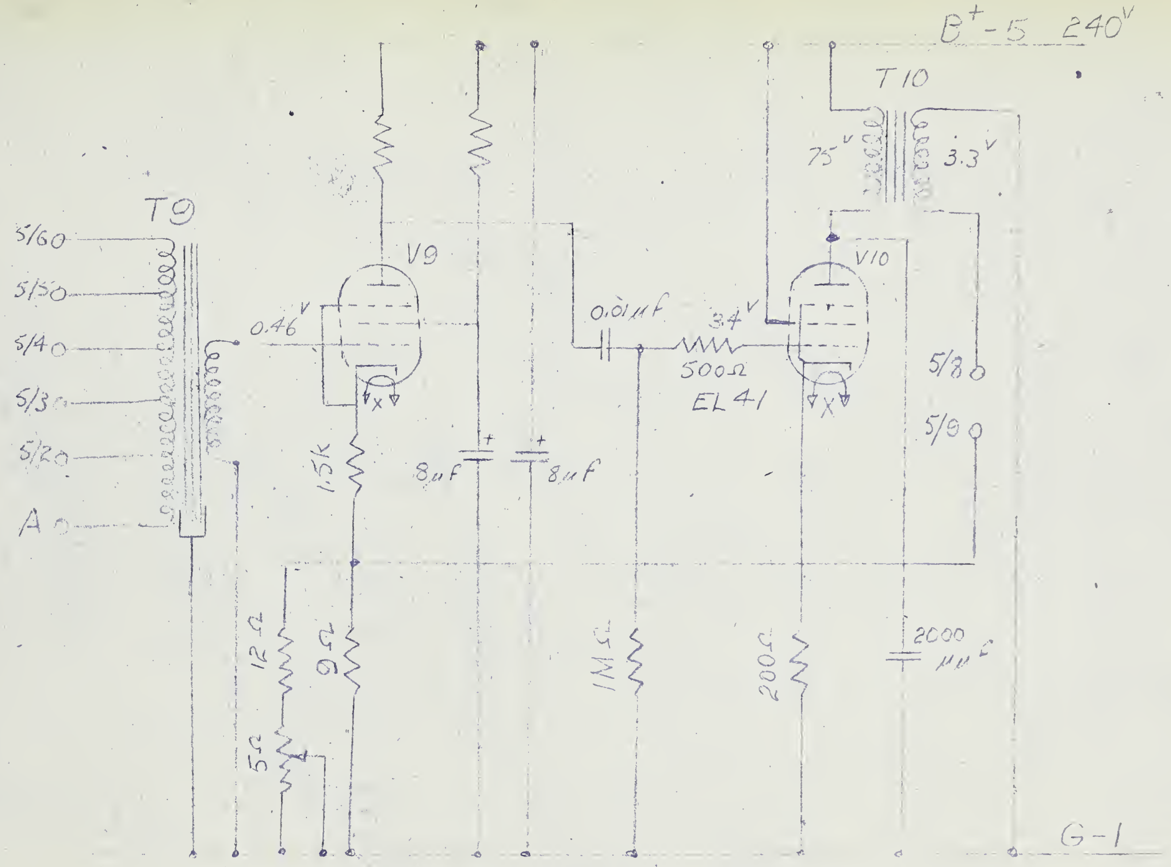
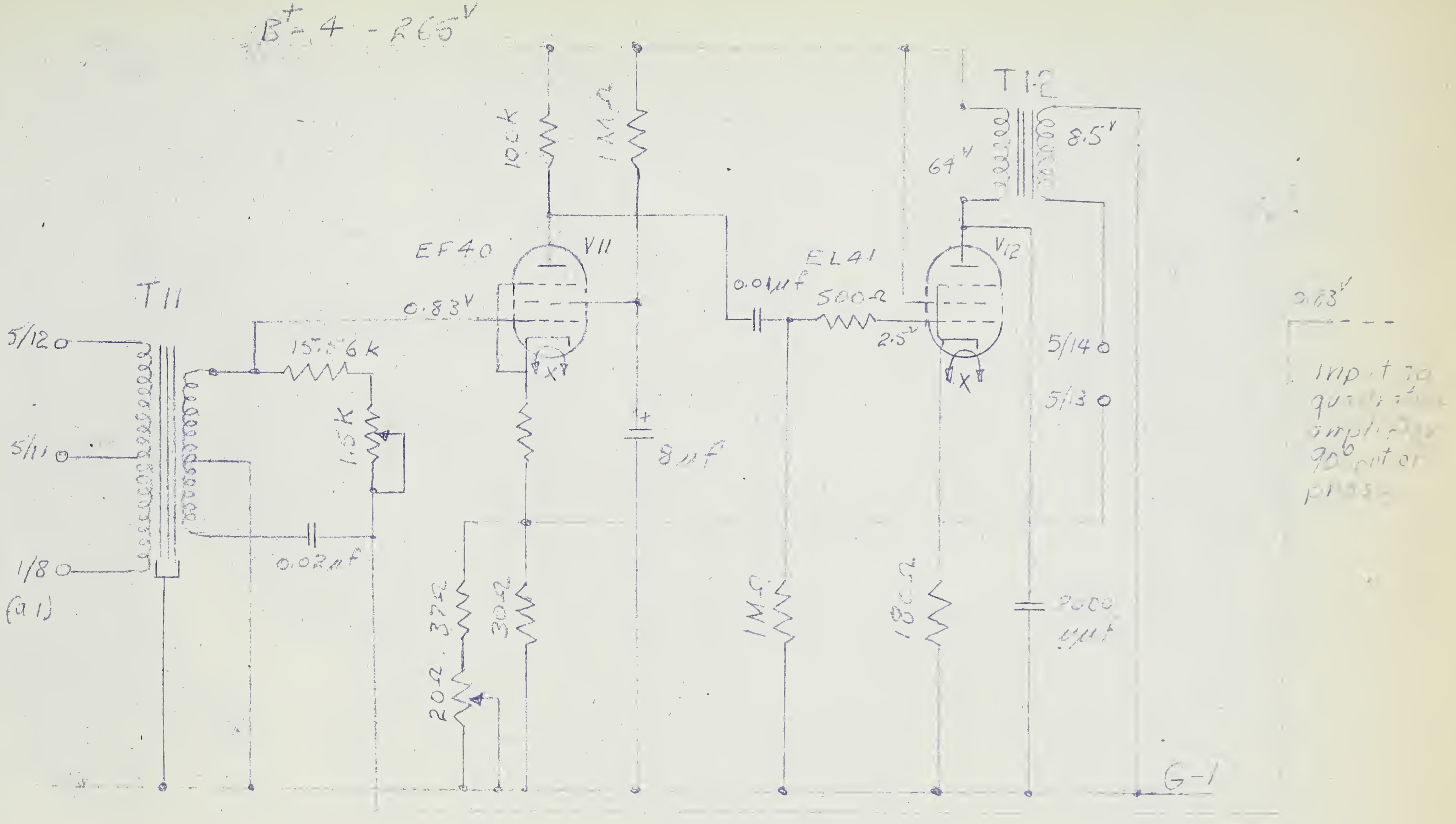


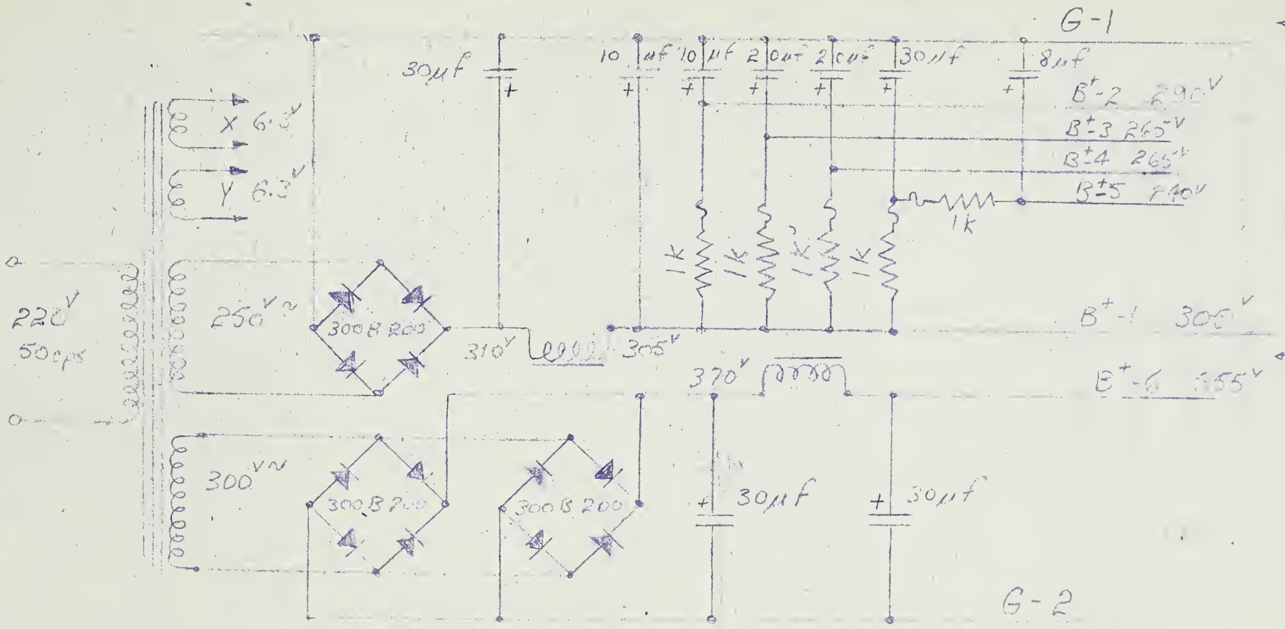
Diagram 32 Output Amplifier



Diag 33 - Contraves Current Amplifier



Diag. 34 - Contrast Potential Amplifier



Another section similar to this is required for the E and A units

Diag 35 Contraves - Rectifier

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